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Managing Sequential Innovation: Product Design, Sourcing and Distribution Decisions

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Managing Sequential Innovation: Product Design, Sourcing and Distribution Decisions

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To my parents Vijaya and Chandru

for their love and support.

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Managing Sequential Innovation: Product Design, Sourcing and Distribution Decisions

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Sequential Innovation involves the serial commercialization of improving products based on technologies that improve over time. In many industries such as semiconductors, electronics and computers, fundamental advances have presented firms with opportunities to substantially improve their product's capabilities in very short periods of time. Customers who invest in these products may, however, react adversely to rapid improvements that obsolete their previously purchased products. In the case of breakthrough products that create categories of their own, potential consumers might even be unaware of their own valuation for new products. In this dissertation, I identify and analyze some means by which a firm can engage in sequential innovation in the face of such apprehensions. In particular, I focus on three aspects of product development that have important implications for its eventual success in the market: product design, sourcing of components and distribution channels.

In the first essay, motivated by an emerging trend in industrial markets, I analyze the role of modular upgradable designs in managing the introduction of rapidly improving products. I show that modular upgradability can reduce the need for slowing the pace of innovation or foregoing upgrade pricing. In the second essay, I study a dual set of challenges that arise for the modular innovator in the presence of strategic consumers and suppliers. The firm's ability to credibly signal its future design strategy could be adversely affected under various sourcing arrangements for peripheral components of the modular product. Even when consumers strategically plan their purchases while taking into account the firm's incentives, they often have limited understanding of their own valuation of a product before they buy it. In the third essay, I consider the role played by channels of distribution that play an educational role when selling sequentially improving products to such consumers who are uncertain about their preferences. The contribution of this dissertation is to formalize the sequential innovation problem and propose solutions that can help firms in synchronizing product development decisions with customers and other value-chain partners.

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Chapter 1

Executive Summary

Sequential product introductions are regarded as the primary source of sustainable growth and profitability in many industries where production and distribution of goods have become decentralized and commoditized. These are often powered by improvements in underlying technologies that unravel in time in a dynamic manner and present a unique set of challenges. Yet, much of the product development literature has focused on the level of single projects or a product line at a given point in time. The ramifications of constant technological flux are felt at all levels of a firm's operations - from cultivating a nimble research environment to designing adaptable products to creating agile and reliable distribution mechanisms. While the number and complexity of problems confronting a product manager has exploded with the rapidity of innovation in various industries, there is a dearth of research and discussion focusing on intertemporal innovation. Insights based on analysis of cross-sectional innovation models are limited, and often turn out to be inapplicable, in understanding and managing sequential innovation. In this dissertation, I take a longitudinal perspective of products based on improving technologies, and investigate the importance of coordination between various organizational functions in determining the ultimate success of these products. In particular, I focus on joint decision-making with respect to product design and development, sourcing strategies for components and selection of distribution channels for products that improve over time.

Sequential introduction of improved versions are routine for several product categories, particularly electronics and software (PC Magazine, 2003). This serial commercialization of improving technologies, whose performance improves over time not only in absolute terms but also in customer-discounted terms, is referred to as *Rapid Sequential Innovation* (RSI). We know, both from our own experiences as consumers of technology products and from prior research, that consumers will find unpalatable the speed of upgrades necessary to follow the trajectory of such rapidly improving technologies. What can an innovator do to bring valuable consumers along the technology path as the product itself improves? In my first essay, I show that contrary to suggestions in the marketing literature, addressing this reluctance is not a matter of restraining the pace of innovation, but rather an issue of coordinated product design and pricing. In particular, the key to ensure that consumers upgrade products at the natural rate of improvement is to offer *modular upgradability* through product design. The approach in this essay is to view the commercialization of rapidly improving technologies as a combination of three separate, but related steps: product design, introduction timing, and pricing (going beyond the last pricing step considered in the prior literature). Based on an industry example, I also distinguish between two design and sourcing options that firms employ. Modules that do not change over time may be provided directly to the customers as an off-the-shelf open-market commodity (Modular Non-Proprietary design), or by the focal firm (Modular Proprietary). The result that modularity can be an important vehicle for value under sequential innovation underscores the importance of taking design and introduction timing into consideration and linking them with pricing while launching an improving product family. Another interesting finding is that in many instances optimal launch times are advanced under a modular architecture; this also highlights a previously ignored demand side advantage to modularity.

However, such a modular product design approach poses a dual set of challenges to the firm in the presence of forward-looking consumers and strategic suppliers. A time-inconsistency problem is created for the firm when consumers with foresight question if the future versions of the product design would continue to be modular upgradable. This is particularly damning because the additional value created by modular upgradability is not preserved unless future versions of a product are also modular. Suppliers of stable subsystems may also take advantage of such a modular approach and seek to appropriate more of the gains from product improvement. These pressures create a two-pronged design inconsistency problem for a monopolist selling improving subsystems, which I formalize and offer an integrated product-design and module-pricing based solution. First, I identify product introduction and market segmentation decisions that help a firm mitigate the time inconsistency with consumers, and derive the optimal development investment made by the seller under these circumstances. Next, I examine how the seller of an improving subsystem must deal with strategic suppliers of stable subsystems. Specifically, the firm must coordinate its design and pricing decisions and innovate at a faster pace to ensure that a strategic supplier's incentives do not cause consumer regret. This interaction between strategic suppliers and consumers offers a potential explanation for why many technological firms engage in rapid sequential innovation despite the possibility of creating consumer regret. These results lead a more nuanced understanding of the development decisions made by firms who serve strategic consumers in the presence of strategic suppliers of components.

Much of the literature on product development, and particularly recent works on sequential innovation, typically ignore an important facet of new products that improve rapidly over time. When new product categories burgeon and improve rapidly, uninformed consumers might not have the opportunity to experience a sample and discover their valuations for the performance attributes of the product. This lack of complete preference awareness by consumers could have profound implications for how sequentially improving products. Faced with this problem, innovators in several industries depend on channels of distribution that specialize in communicating the salient aspects of a product without forcing consumers to purchase a unit. For example, a product manager at a printer manufacturer uses QVC and trade shows as effective avenues for demonstrating and distributing products to uncertain consumers. We refer to these channels of inference as *Infermediaries*. In spite of the opportunity infermediaries create by providing a product-information bundle for the uncertain segment, they are not always used by manufacturers. This gives rise to some important questions about channel selection: Are infermediaries valuable channel partners under all circumstances? What firm, product and market characteristics are most favorable for employing infermediary distributors? To answer these questions, I consider a market segmented along two dimensions: true preference for product quality and certainty of preference. The analysis shows that revealing true valuations to consumers before they purchase a product could be counterproductive to the manufacturer's cause depending on the pace of innovation and composition of the market. Most importantly, the analysis gives rise to a first-order understanding of the exact role of an infermediary channel in distributing new and improving products.

The rest of this dissertation is organized as follows. The literature related to the product design, sourcing and pricing issues is summarized in Chapter 2. Coordinated product design and pricing for rapidly improving products is discussed in Chapter 3, followed by the discussion of commitment issues and sourcing options in Chapter 4. In Chapter 5, we discuss the channel selection problem for the innovator facing uncertain consumers. We conclude with a discussion of our results and managerial implications in Chapter 6.

Chapter 2

Literature Review

New Product Development (NPD) is an indispensable, fundamental activity for all organizations involved in the production of goods and services. Deservedly, product development has attracted significant attention in the academic and practitioner literature. NPD efforts are increasingly focused on sequential product introductions, which are regarded as the primary driver of growth and sustainability in many industries. Rapid advances in basic sciences, technologies for coordination and decentralization of design and development have quickened the pace of sequential innovation in categories ranging from automobiles to electronics to services (Business Week, 2006). The vast body of research on NPD, however, has paid limited attention to the new managerial challenges created in developing sequentially improving new products.

In this dissertation, I broach, formalize and analyze some of these issues in detail, with particular emphasis on the coordination between various organizational functions. In doing so, I take a the view of NPD as the "transformation of a market opportunity into a product available for sale" (Krishnan and Ulrich, 2001). In this chapter, I review three different areas in the literature that are related to the ideas presented: Sequential innovation, Product

Architecture, and Channel Design.

2.1. Sequential Innovation

Since an improved version of a product competes with previously versions of itself that are available in a market, it is instructive to begin with a brief synopsis of such intertemporal competition. Durable goods manufacturers have been a subject of long-standing interest in the economics literature[1]. Coase (1972) argued that rational expectations of sufficiently patient customers will eliminate the opportunity to sell the good at different prices to customers who value it differently. This competition from goods sold earlier makes leasing a preferable alternative to selling durable goods (Bulow, 1982), and a selling firm also has an incentive to reduce the physical life of an old product compared to a leasing firm (Waldman, 1996). Interference from early sales may be controlled by using mechanisms such as buybacks, planned obsolescence or trade-ins (Fudenberg and Tirole, 1998). These tactics are often not feasible leading to excessively slow product introductions (Fishman and Rob, 2000). This work proposes product design as an essential ingredient in the sustenance fast new product introduction.

When customer valuations of a product are not uniform, a durable product may be priced dynamically to achieve intertemporal price discrimination (Stokey, 1979). A firm can also use a product line to discriminate in such

[1]Dhebar (1994) provides a more detailed review of this literature.

a market, but low end customers exert a negative externality on the firm's ability do so (Mussa and Rosen, 1978). The effects of cannibalization on new product introduction have been studied for static and improving technologies by Moorthy and Png (1992) and Bhattacharya et al. (2003) respectively, and later in the context of development intensive products by Krishnan and Zhu (2006). This research adds to this literature by studying the tradeoffs in timing product launch when the core technology available is improving rapidly.

Although I discuss sequential innovations in general, Chapter 3 is motivated by critical problems faced by rapidly-improving products in the market, which have not received sufficient attention. Dhebar (1994) highlighted the problems faced by a monopolist firm in intertemporally discriminating among its customers in the context of rapid sequential innovation. Innovators have to be mindful of customers' distaste for rapid improvements that would make an earlier purchase obsolete. Unfortunately, in most industries, especially those that involve nascent technological standards, delaying commercialization of advanced technologies is not an option due to a number of reasons. First, product quality in relatively new industries is closely tied to the underlying technology's properties, knowledge about which could be public. A second characteristic of such technologies is the opportunity for smaller businesses to enter the market if a monopolistic firm fails to offer the best possible quality. Third, selling a durable product with little or no improvement over time can expose the monopolist firm to competition from second hand markets in later periods (Coase, 1972; Bulow, 1982).

Kornish (2001) showed that by foregoing its ability to offer its preferred or installed base customers a special upgrade price for the improved product, the firm will be able to signal to its customers that their purchase decisions in the first period will not be unduly used to the firm's advantage. However, it is not clear if either rapid innovation or intertemporal price discrimination should belong to the set of objectives of a profit maximizing firm. To address these issues, I allow the firm to decide the number of products to launch and rate of improvement in addition to determining the optimal product architecture.

It should be noted that while Chapter 3 deals with industrial consumers who are concerned about installation costs and learning issues, Chapter 4 focuses on consumers who derive value by using these products at a personal level. For a recent overview of adoption decisions of organizations that buy improving technologies used in production of other goods and services, see Hoppe (2002). Optimal pricing policies for a firm selling improving technologies to competing manufacturers have been developed by Erat and Kavadias (2006). The focus in this literature has been to capture decisions made by profit maximizing agents who adopt (industrial) technologies and potentially compete among themselves, while I concentrate on rational utility maximizing customers. In Chapter 4, and to a lesser extent in Chapter 5, I also consider strategic interactions of the manufacturer-retailer supply chain form. In a related paper, Villas-Boas (1998) has discussed how such interactions might influence the structure of the product line (Villas-Boas, 1998).

2.2. Product Design and Architecture

There exists a growing body of literature on the design of new products. Product architecture specifically is the scheme by which the performance quality (function) of a product is allocated to physical components (Ulrich, 1995), and has important implications yet to be uncovered in the literature. In a modular product, the mapping from performance quality to components is one to one. Modularization adds to the real option value of any product's design; while integral products have to be redesigned for each application, modular architectures can be used as platforms in several variations of the basic product (Langlois and Robertson, 1992; Baldwin and Clark, 2000). Product modularity also induces economies of scale due to component commonality, and these production efficiencies have to be factored into product line decisions (Kim and Chhajed, 2000; Desai et al., 2001). Other advantages of modularity arise from the ability to reuse previously designed components, save costs in logistics, and make product variety profitable (Fisher et al., 1999; Kekre and Srinivasan, 1990). A more recent and detailed survey of the literature of modularity can be found in Mikkola and Gassmann (2003). In spite of the advantages of modular systems, an integral product architecture is preferable under certain circumstances due to the adverse impact of modularization on product design (Ulrich and Ellison, 1999) .

Modular architecture has been embraced by the industry for two main reasons (The Wall Street Journal, 1991). First, modular innovation can be more effective than systemic innovation because of the ability of the organization to transfer accumulated knowledge across successive generations of new products, resulting in longevity of the platform and wider variety of models (Sanderson and Uzumeri, 1995). Second, customers find the task of adjusting to modular innovations easier than coping with radical systemic changes(Sanchez, 1999).

Modular upgradability is a specific form of modularity, in which the product is designed to be upgradable in modules, thereby allowing for longitudinal component reuse. Upon deciding to make its product upgradable in modules, a firm must still choose between proprietary and industry-standard alternatives to source its modules (Morris and Ferguson, 1993). This choice becomes relevant when industry-standard subsystems can become substitutes for a firm's components. Garud and Kumaraswamy (1993) investigate Sun Microsystems' architectural strategy and conclude that an open (non-proprietary) architecture encourages manufacturers of complementary products and even rivals to make and support compatible products. Chapter 3 identifies the value from a market and operational perspective of using non-proprietary industry-standard components in conjunction with firm-proprietary improving modules.

2.3. Channel Design and Product Valuation

One of the central assumptions in all of the research that have been discussed above is that as long as a firm's products are superior to others that are available (or will become available in the future), the better product will be judged fairly and accurately in the marketplace. In Chapter 5 of this dissertation, I consider the case of new-to-the-world products that consumers are unable to evaluate their preferences for.

This type of *valuation uncertainty* has been considered by researchers in economics, who explain its presence in different ways. In his seminal work, Nelson (1970) describes how *experience* goods are quite different from search goods because of the fact that consumers will unable to judge their own marginal utilities for the service they provide sans a first-hand experience of its attributes. Interactions with a product manager at a major printer manufacturer suggests that, in this aspect, a new dimension printer may not be too different from a new model of running shoes. As an alternative explanation for why consumers may not be able to thoroughly evaluate a product before buying it, Milgrom (1981) postulates that it is perhaps a result of the limited information consumers may have about certain liabilities of a product; these hidden factors, referred to as *shrouded attributes*, are commonplace in several goods as well as services. A third explanation for this phenomenon - found in 'advance selling' literature - is that the lead-time between the time at which an object or a service is purchased and the point of time at which it is used creates significant uncertainty about its value at the time of purchase (Xie and Shugan, 2001). While I do not delve into the details of the origin of such uncertainty, Chapter 5's focus is on the challenge faced by a sequential innovator managing a new product-category that is evolving over time.

Prior researchers have also considered the effects of such uncertainty on the decisions made by producers and consumers alike. A couple of recent works that extend the above concepts highlight the importance of considering this issue. First, Gabaix and Laibson (2006) discuss the importance of strategically considering whether or not shrouded attributes should be revealed under competition. Second, Lariviere and Alexandrov (2007) show why restaurants might offer reservations when consumers are uncertain about their future valuations. Both, as do other papers that consider this issue, consider how the firm might exploit (or react to) value uncertainty. The analysis in this dissertation extends this research in several ways. First, I take truly intertemporal view of the phenomenon in considering the decision-making of a firm that sequentially innovates, and that of consumers who repeated evaluate these product. Second, I incorporate how consumers' learning from prior purchase decisions might affect their confidence in making subsequent decisions. I also consider the role certain channels may play in distributing new-to-the-world products to uncertain consumers.

The only prior work that has meaningfully considered the repeat purchase behavior in a context quite similar to this dissertation was by Cremer (1984), who evaluated the benefit of offering introductory purchase benefits when consumers are unsure if the product is valuable or not. However, Cremer too considers only one vintage of a product that is being sold over several periods. As we will see in Chapter 5, the sequential innovation problem is quite richer. In that chapter, I propose that certain channels are very effective in allowing consumers to infer their valuations for the product without forcing a purchase, and identify conditions under which they are valuable as distributors. This line of comparing modes of distributions is also related - albeit tenuously - to the emerging literature that studies simultaneous distribution through online and brick-and-mortar channels (for example, Cattani et al., 2006).

Chapter 3

Design Architecture and Introduction Timing for Rapidly Improving Industrial Products

3.1. Introduction

Major technological advances in the physical and biological sciences and an increasingly digitally networked world-wide R&D community drive rapid quality improvements in many product categories. It is well known that speeds of microprocessors have increased substantially over the last decade, and Intel has emerged as the dominant firm by maintaining a rapid pace of innovation according to *"Moore's Law"* (Newsweek, 2002). Sequential introduction of improved versions are also routine for many other electronics and software products (PC Magazine, 2003). The serial commercialization of improving technologies, whose performance improves over time not only in absolute terms but also in customer-discounted terms, *Rapid Sequential Innovation* (RSI).

Firms engaging in RSI face certain unique challenges in persuading their customers to purchase their current product rather than wait for an improved version. Dhebar (1994) showed in a two-period setting that under RSI when rational customers anticipate a monopolist seller's opportunistic pricing behavior, the firm's profit-maximizing pricing scheme results in no sales of one of the versions of products. Facing rapid improvements, prior customers may regret their buying decision and prospective customers could delay their purchase timing. This forces a monopolist - who primarily uses prices to segment markets under rapid sequential innovation - to consider restraining the pace of innovation. In a subsequent paper, Kornish (2001) showed that the firm can partly address this issue of customer balking by committing to not offering special upgrade prices for the improved second-period product. While a firm may avoid artificial introduction delays by placing restrictions on the way products are priced, prior customers have come to expect special upgrade prices in many product categories (such as application software and other technology products). With customer relationship management (CRM) systems in place, firms also increasingly use this data and special upgrade discounts to attract existing customers. Under these circumstances, a monopolist firm may not be able to credibly commit upfront that it will not offer special upgrade prices in the future.

In this chapter, I study a product architecture based approach that expands the firm's degrees of freedom to include product design decisions for managing the special challenges associated with rapid sequential innovation. Specifically, I study the case when a firm considers partitioning rapidly advancing products into improving and stable (industry-standard) modules, enabling itself to focus on its core skills and convince customers that their investments in products won't be totally obsoleted in short periods of time. Products thus designed, whose performance can be improved by replacing a minimal set of components are termed *Modular Upgradable* (MU).

The modular upgradable approach is gaining popularity with many industrial products such as rackable computer systems, semiconductor photo-lithography equipment, and optical inspection systems. In each of these categories, customers are able to assimilate sequentially improving technologies by buying specific modules, without obsoleting their entire system purchased earlier. In the computer industry, firms such as IBM and Rackable systems have been advancing the trend of modular upgradability, which allows their customers to selectively and incrementally upgrade their system. In the optical inspection market, for example, the firm ViTechnology designed and launched its new series of products so that the camera modules can be easily upgraded to meet future accuracy requirements for inspections. Similarly, in the semiconductor photo-lithography equipment segment, industrial customers such as Intel and AMD are able to upgrade their systems in a modular fashion by buying from firms such as ASM Lithography, Canon, and Nikon. Given the escalating cost of such equipment and the commoditization of end markets, customers prefer the productivity gains and cost savings achieved by upgrading in modules even while incurring the effort involved in installation and modular upgrades.

The approach in this chapter is to view the commercialization of rapidly improving technologies as a combination of three separate, but related steps: product design, introduction timing, and pricing (going beyond the last pricing step considered in the prior literature). Specifically, I focus on the impact of selecting different product architectures and component sourcing options on optimal introduction timing and pricing. Customers who purchase these products do so for productivity improvements, but may incur both costs of initially integrating and subsequently upgrading the modules. In many instances, it is found the firm may gainfully introduce the new product earlier without adhering to constraining price commitments by using a modular product architecture. A central finding of this work is that combining a modular upgradable product architecture with pricing can alleviate the effects of adverse customer reaction to rapid obsolescence and improve firm profits in a wide range of situations. While such an approach might also apply to consumer markets, there are some additional issues which limit the use of modular upgradability that I discuss in the final section.

Based on the industry example, it is also possible to distinguish between two design and sourcing options that firms offering modular upgradable products employ. Modules that do not change over time may be provided directly to the customers as an off-the-shelf open-market commodity (Modular Non-Proprietary design), or by the focal firm (Modular Proprietary). Both these approaches are prevalent - for example in the semiconductor photo-lithography equipment market, while firms such as Nikon and Canon largely develop the various component modules in-house, the European firm ASML increasingly offers non-proprietary modular systems, in which customers can obtain components from other manufacturers[1]. Similarly, Intel processors - which are

[1]One of ASML's stated business strategies is to offer "continuing improvements in produc-

Figure 3.1: Semiconductor Wafer Stepper with an Upgradeable Projection Lens Module

known to improve rapidly - can be used in combination with motherboards manufactured by several other firms. I formalize and analyze each of these proprietary choices, identify optimal prices for the sequence of products, and derive conditions under which either product introduction approach is appropriate.

The results underscore the importance of taking design and introduction timing into consideration and linking them with pricing while launching a product family. The finding that in many instances optimal launch times are advanced under a modular architecture also highlights a previously ignored demand side advantage to modularity. The analysis proceeds in two parts. Initially, the timing decision are ignored to obtain optimal prices for different design choices, where the concept of Sub-Game-Perfect equilibrium is

tivity"... by "introducing advanced technology, based on the modular, upgradeable design of" ASML products (ASML, 2001). ASML's newly introduced stepper system TWINSCAN^{TM}, is also a modular upgradable system comprised of components from several other manufacturers (ASML, 2005).

invoked. Later, the introduction timing decision for the different scenarios is endogenized. The rest of this chapter is organized as follows. The constructs and formal model are presented in Section 3.2. The analysis and main results are presented in Section 3.3 and Section 3.4. I conclude with a discussion of analytical results and managerial implications in Section 3.5.

3.2. Model Setting and Description

In this section I describe the sequential introduction problem faced by a monopolist firm that has developed an early version of the product $\mathcal{P}_1$, and is in possession of an advanced technology which could be transformed into a new product $\mathcal{P}_2$ with improved performance quality. I first discuss the specific assumptions and their implications before providing a timeline for interaction between the firm and its customers in closing. I use the word *customer* to refer to an industrial customer that purchases the product, and *firm* to refer to the developer who sells these products.

3.2.1 Modeling Assumptions

The products under consideration (both hardware or software) are purchased by the industrial customers for productivity improvement. The value a customer derives from the productivity improvement of a particular version of the product depends on the version's basic performance quality, the duration for which it is used, the benefits of learning that accrues by using, the rate at which future benefits are discounted, and the effectiveness with which the customer uses the product.

- *Productivity Benefits and Learning by Customers.* The product of quality q provides an instantaneous productivity, or output per unit of time, given by $z(q,t)$. In addition, customers realize productivity improvements over time as they familiarize themselves with the product's capabilities and gain expertise in applying them. Specifically, they experience an instantaneous rate of learning, which is represented as L. When a customer uses a product with a productivity of z per unit time for a duration of t, learning-by-doing increases the per unit productivity to ze^{Lt}. For notational simplicity, customer learning that occurs over a period of length t is captured through the parameter $\gamma(t) = e^{Lt}$. Let the output over a period of duration t of a product of quality q is given by $x_q(t)$.

- The firm and customers may borrow at an interest rate of r. Productivity benefits and payments that are delayed by a period of length t are discounted by a factor of $\delta(t) = e^{-rt}$. $x_q(t)$is related to the the maximum lifetime utility of the product $f(q)$, the learning and discount rates through Equation 3.1.

$$x_q(t) = (1 - \gamma(t)\,\delta(t))\,f(q) \tag{3.1}$$

  To ensure that customers who buy the first version do not trivially reject the second version, attention is restricted to product categories where the learning rate does not exceed the rate of innovation. Specifically, I assume that $\gamma f(q_1) < f(q_2)$. Further, to ensure that $f(q)$ is bounded, I assume that $r > L$.

- Industrial customers that may buy the product differ in their ability to assimilate and apply the product's offerings to improve their productivity. This ability, measured by index v, is uniformly distributed between 0 and 1 [2]. The lifetime value a type v customer derives by using the product depends on the quality of the product q_t. $W(q, v)$, the reservation price of customer v for a product of quality q, is given in Equation 3.2 below. When the improved product is launched, given that v has $\mathcal{P}_1$, $v(f(q_2) - f(q_1))$ is customer willingness to pay for $\mathcal{P}_2$. The function $f(q_t)$ represents the benefit of a unit of product quality[3].

$$W(q_t, v) = vf(q_t) \tag{3.2}$$

- Customers incur an installation cost of C_I when a product is installed and an an upgrading cost C_U when upgrading the product. In industrial contexts, product installation requires assembling various modules together at the site of installation, re-calibration of sensitive equipment, and customization. However, while customers are required to assemble the modules for each installation in some product categories, other manu-

[2]While the most important results are valid under general customer distributions and valuation functions, the uniform distribution is used to simplify the presentation.

[3]In a more general multi-period setting, if at time t, customer v owns a product launched at $\tilde{t}$, the willingness to pay is only $v(f(q_t) - f(q_{\tilde{t}}))$.

facturers also offer installation services for new buyers[4]. These two cases are modeled separately. In Section 3.3.4, I consider the effect of these cost parameters C_I and C_U on the optimal design and pricing decisions for the various modules.

- It is assumed that the marginal production costs are negligible compared to the fixed costs of product development, which is increasingly the case in knowledge-intensive industries. Product development costs depend on t_d, and the relationship is presented in Section 3.4.2.

Consumption and pricing decisions depend on the rate of sequential improvement. *Rapid* sequential innovations are different from more gradual improvements since performance quality of $\mathcal{P}_2$ exceeds that of $\mathcal{P}_1$ even in present value (Equation 3.3). Second hand markets are unknown for industrial products that motivate this work. Rapid sequential innovation, by rendering older versions obsolete, further reduces the viability of markets for used goods. This assumption that second hand markets do not exist is useful to keep the focus on the architecture-innovation interaction.

$$\begin{array}{ll} \text{Rapid Improvement} & \delta f(q_2) > f(q_1) \\ \text{Gradual Improvement} & \delta f(q_2) \leq f(q_1) \end{array} \tag{3.3}$$

The firm does not condition prices on previous purchases. Therefore, no assumptions are made on the level of anonymity involved in repeat purchases.

[4]Firms commonly offer both product packages and separate modules simultaneously. Customers can avoid incurring the installation cost by purchasing packaged products.

Fudenberg and Tirole (1998) analyze the effect of anonymity on the sequential pricing strategies of the firm, but unlike this work, they (i) do not consider the impact of product architecture on consumption, and (ii) restrict themselves to gradual rates of product improvement.

The sequence of the customer's and firm's actions is shown in Figure 3.2. The firm first makes its decisions about the inter-generational product architecture (integral or modular architecture) and launches the first period product $\mathcal{P}_1$. Customers then make their first-period *purchase* or *wait* decisions based on the price, quality, and the architecture of the first-period product and the expected price and quality of the improved (second-period) product. In accordance with the prior work on rapid sequential innovation, I assume all customers have the same expectations for price and quality of the second-period product. In the second period, the improved product $\mathcal{P}_2$ is released based on the architectural decision made earlier at a price that the firm finds optimal. Customers base their second-period purchase decisions on the announced prices and qualities of the improved product. Prior research on this topic did not include the architectural decision that I consider for the firm at the beginning. The interaction between architecture and pricing offers an additional degree of freedom, which forms the point of departure for this research.

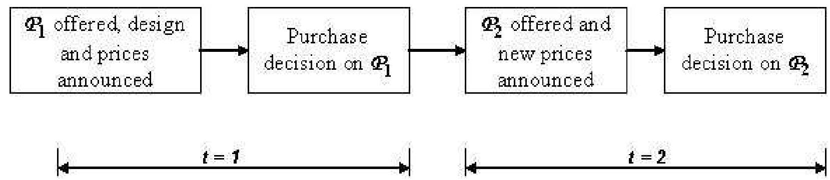


Figure 3.2: Timeline of decisions

3.2.2 Architectural Choice and Modular Upgradability

The literature on rapid sequential innovation assumes that each version of the product is an integral unit. Further, the impact of not launching the inferior version is also not considered. Here both assumptions are explicitly relaxed to capture demand-side forces that shape a product's evolution and its architecture over time. The salient characteristics of sequentially improving modular products are two-fold.

(a) *Product Partitioning*: The product consists of physically and functionally separable component subsystems. A modular design approach involving a one-to-one mapping from functions to components allows for such product partitioning (Henderson and Clark, 1990; Ulrich, 1995).

(b) *Localized Improvements*: Quality improvement is *localized* in only some of the component subsystems. By this I imply that the older version of the product/system can be upgraded by replacing only a subset of components.

Each product $\mathcal{P}_t$ of the sequence is an aggregation of components; the relationship between functionalities of the different components and performance qualities is captured by the operator $\mathcal{Q}(\mathcal{P}_t)$. Property 3.2.1 is satisfied by this sequence of products when it is Modular Upgradable.

Property 3.2.1. Modular Upgradability

The sequence of products $\mathcal{P}_t$ *is modular upgradable if there are non-empty partitions* $\mathcal{I}_t$ *and* $\mathcal{S}_t$ *such that:*

1. **Modularity**: $\mathcal{I}_t \cup \mathcal{S}_t \equiv \mathcal{P}_t$ *and* $\mathcal{I}_t \cap \mathcal{S}_t \equiv \emptyset$, $\forall\, t = 1..T$
2. **Localization**: $\mathcal{Q}\left(\mathcal{P}_{t+1}\right) = Q\left(\mathcal{I}_{t+1} \cup \mathcal{S}_t\right)$, $\forall\, t = 1..T-1$

Instead of considering quality enhancements at the component level, I take a consolidated view of the product and assume that each version is separated into a *Stable Module* ($\mathcal{S}_t$) and an *Improving Module* ($\mathcal{I}_t$). I consider modular product systems in which all the significant improvement is localized on a subsystem $\mathcal{I}_t$ produced by the monopolist firm. As mentioned earlier, a two period model is considered ($T = 2$). Note that localization implies that the stable module does not undergo major functional changes and will be represented by $\mathcal{S}$ ($\mathcal{S} \equiv \mathcal{S}_1 \equiv \mathcal{S}_2$). The different modules are produced at constant marginal costs (c_1, c_2 and c_s for $\mathcal{I}_1, \mathcal{I}_2$ and $\mathcal{S}$ respectively). Though the general model is suited for multiple dimensions of quality, I focus on a one-dimensional measure q, which can either be a weighted measure of the constituents or the most dominant element of $\mathcal{Q}$.

Modularization also has the potential to affect the quality of the product. Technologically, the product may become bulkier and creation of additional interfaces may lower product quality (Baldwin and Clark, 1997; Ulrich and Ellison, 1999). Also, a customer choosing to upgrade the improving module may experience a loss of quality due to additional assembly. These negative effects of modularity by explicitly considered through a loss of quality parameter, $\alpha \in [0, 1)$.

Suppose the products introduced in the two period model are of qualities q_1 and q_2 when designed as an integral system. But in a modular system, the quality of the improved version is reduced to q_2^{α}.

$$\frac{\partial f(q_2^{\alpha})}{\partial \alpha} < 0$$

The impact of this quality loss is analyzed in following sections. To consider RSI products alone, in the discussion of modularity, attention is limited to combinations of α and δ_c such that:

$$\delta f\left(q_2^{\alpha}\right) > f(q_1)$$

A simple form is used in the numerical analysis in section 3.4.

$$f(q_2^{\alpha}) = (1 - \alpha) f(q_2)$$

The firm decides whether the product sequence would be modular as described above, or if a quality-optimized integral product will be independently developed in each period. If the modular architecture is selected, there are two fundamentally different design alternatives for the modular product described above. $\mathcal{I}_t$ can be designed to work with a stable module $\mathcal{S}$ manufactured by other firms or only with that made by the focal monopolist firm. To investigate the influence of modular upgradability in these two cases, I distinguish between *Proprietary* and *Non-proprietary* modular upgradable products. In the rest of the section, the pricing possibilities and cost side effects for each of these product architectures are described.

3.2.2.1 Proprietary Modular Upgradable Systems (MP)

When customers must purchase both the improving and stable modules from the same firm, the firm is said to follow a proprietary modular upgradable approach. The improving modules, $\mathcal{I}_t$, are uniquely designed for each product, $\mathcal{P}_t$. Both versions of $\mathcal{I}_t$ are designed to be compatible with the firm's own stable module, $\mathcal{S}$.

The two versions of the improving modules, $\mathcal{I}_1$ and $\mathcal{I}_2$ are priced at p_1 and p_2 respectively. $\mathcal{S}$, which can be used in conjunction with any improving module, is sold at the same price p_s (at margin $p_s - c_s$) in both periods. If the price of $\mathcal{S}$ is allowed to change, the firm holds the ability to price the whole product opportunistically in the second period and hence continues to face the same problem associated with selling a sequence of integral products. The primary interest, therefore, is in situations in which p_s is unchanging between periods.

While modularity allows customers to retain the stable module, replacing the improving module often involves tedious and costly procedures. I model this upgrading effort as a cost C_U incurred by a customer who buys the first version and upgrades in a modular fashion later. Since several manufacturers offer packaged products for new buyers and improving modules for upgraders, I assume that the upgrading cost is not applicable to customers who buy either the first or the second version exclusively. The results presented, however, can be easily extended to a more general case.

Let $\mathcal{D}_0, \mathcal{D}_1, \mathcal{D}_2$ and $\mathcal{D}_u$ be the set of customers who do not buy any product, buy only the first version, buy only the second version, and those who buy both versions respectively. Let D_0, D_1, D_2, and D_u be the corresponding number of customers. In a proprietary system, the firm gets revenues from sales of improving and stable modules, but delayed benefits are discounted. The firm's problem in the second period is:

$$R_2^*(p_s) = \max_{p_2} \left(\left((p_2 - c_2) + (p_s - c_s) \right) D_2 + (p_2 - c_2) D_u \right) \tag{3.4}$$

While launching the early version, the firm should be mindful of the effect p_s will have on the later sales as well. The firm's first period problem is:

$$\Pi_{MP}^* = \max_{p_1, p_s} \left(((p_1 - c_1) + (p_s - c_s))(D_1 + D_u) + \delta R_2^*(p_s) \right) \tag{3.5}$$

To make the results comparable to the existing literature on RSI and to achieve compact analytical expressions, cost savings and inter-product-line substitutability are ignored in the formulation.

A commitment issue still challenges the firm designing MP systems. In an attempt to sell a higher volume of non-improving components when the advanced version is launched, the firm can willfully renege from its previous commitment to make future improving modules compatible with old stable modules. Firms with a weak or insufficient record of credibly upholding these compatibility commitments may use the following architectural approach.

3.2.2.2 Non-Proprietary Modular Upgradable Systems (MN)

When the product is designed so that the stable module is a commodity that can be purchased from the open market, the firm is said to follow a *non-proprietary modular upgradable* approach. I consider the case of the general purpose module that will be produced and supplied competitively by many firms (at price p_s); this is characteristic of the desktop computer industry where several competitors supply some basic components with standard interfaces and minimal differentiation, and some components that improve with time are produced by a few manufacturers. An industry structure of this type could also be formed when a manufacturer of a modular system opens up the architecture of its system and/or certain functional, spatial, and compatibility specifications to rivals and partners. The firm sets prices p_1 and p_2 by solving the following problems in the two periods. It foregoes not only the ability to price the stable module but also revenues from selling the stable module. Optimal solutions for the problem 3.6 are found in Section 3.3.3.

$$\begin{array}{ll} \textit{Second Period}: & R_2^*(p_s) = \max_{p_2}\left((p_2 - c_2)\left(D_2 + D_u\right)\right) \\ \textit{First Period}: & \Pi_{MN}^*(p_s) = \max_{p_1}\left((p_1 - c_1)(D_1 + D_u) + \delta R_2^*(p_s)\right) \end{array} \tag{3.6}$$

The external firms, by virtue of experience gained by manufacturing $\mathcal{S}$ as a commodity, may be able to deliver a higher overall product quality through its stable module. For example, customers who purchase ASML's micro-lithography equipment for semiconductor manufacturing are able to upgrade the optical elements by purchasing image-sensing components from Carl Zeiss.

I represent the technological inferiority of completely proprietary systems using the parameter β ($\beta \in (0,1]$). When the non-proprietary choice delivers product qualities q_t, the proprietary solutions, irrespective of the architecture, are capable of delivering only customer perceived quality βq_t.

Often proprietary modular products deliver higher quality than non-proprietary alternatives ($\beta > 1$). In this context, the non-proprietary designs have no value in these cases for firms which have commitment credibility. This uninteresting case is ignored in the rest of the chapter. Though it is quite possible that β is endogenous to technological and market specifications, but reserve its determination for future work.

Selecting, procuring and installing an off-the-shelf stable module entails significant effort and cost for a customer in the non-proprietary case. Each installation of a system results in costs associated with interfacing the open-sourced Stable module with a new Improving module. This cost is denoted by C_I. Note that this installation cost is expended twice by an upgrading customer whereas the upgrading cost C_U is incurred only during the upgrading step.

3.2.2.3 Proprietary Integral Systems

The default option for the firm is to provide an integral product where the stable and improving module are not separable. The advantage is the lack of any quality loss arising from modularity ($\alpha = 0$), and this is the approach that has been studied by prior papers. Specifically, Kornish has shown that the optimal approach is for the firm to not offer special upgrade prices to early buyers. The pricing problem for the firm, which is obtained by adding the constraint $p_s = 0$ in problem (3.5,3.4) above, is shown below.

$$\begin{array}{ll} Second\ Period: & R_2^* = \max_{p_2}\left((p_2 - c_2)\left(D_2 + D_u\right)\right) \\ First\ Period: & \Pi_I^* = \max_{p_1}\left((p_1 - c_1)(D_1 + D_u) + \delta R_2^*\right) \\ & s.t.\ p_s = 0 \end{array} \tag{3.7}$$

If the advanced technology represents a significant improvement over the early version and if the costs of accelerated development are not overwhelming, it might be in the firm's best interest to avoid launching the early version. This is simply obtained by setting $D_1 = D_u = 0$ in (3.7). Note that it is not necessary to modularize the product when only the advanced product is released.

3.3. Model Analysis

The analysis proceeds in two steps. First I identify the optimal prices for proprietary and non-proprietary modular architectures for fixed $t_1$and t_2. Here, the development time ($t_d \doteq t_2 - t_1$) is taken as constant and the corresponding discount and learning factors $(\delta(t_d), \gamma(t_d))$ as given. Later we backtrack and find the optimal launch interval, t_d, available for developing a new product from the improved technology for the different architectures. Reducing a significant part of the analysis to a two-period model allows closer comparison of profits with other strategies suggested in the literature (Dhebar, 1994; Kornish, 2001), while also making the presentation linear.

The firm first derives the demand pattern that will be generated by its prices. Customers anticipate the pricing reactions of the firm in the second period based on their consumption decisions in the first period. To obtain a consistent set of prices, beliefs and consumption decisions, sub-game-perfect solutions are sought. In Sections 3.3.2 and 3.3.3, the focus is on the role of architecture and normalize the installation costs C_I to zero. Subsequently, the analysis is extended to include installation cost in Section 3.3.4.

3.3.1 Modular Design and Market Segmentation[5]

The marginal customer who is indifferent between actions i and j is denoted by v_{ij}. Here, i and j represent the decision pairs described above: $i, j \in 0, 1, 2, u \equiv$ *{do not buy any version, buy in first period only, buy improved version only, buy in both periods}*. Note that a customer can be indifferent between actions i and j, but perform neither. Marginal customers' indices for the modular system are shown in Table 3.1. (v_{ij} and v_{ji} are used interchangeably throughout the chapter.)

Actions	No purchase	Buy $\mathcal{P}_1$	Buy $\mathcal{P}_2$
Buy $\mathcal{P}_1$	$v_{01} = \frac{p_s+p_1}{f(q_1)}$	-	-
Buy $\mathcal{P}_2$	$v_{02} = \frac{p_s+p_2}{f\left(q_2^{\alpha}\right)}$	$v_{12} = \frac{\delta(p_2+p_s)-(p_1+p_s)}{\delta f\left(q_2^{\alpha}\right)-f(q_1)}$	-
$\mathcal{P}_1$& $\mathcal{P}_2$	$v_{0u} = \frac{p_s+p_1+\delta p_2}{\delta f\left(q_2^{\alpha}\right)+(1-\delta\gamma)f(q_!)}$	$v_{1u} = \frac{p_2}{f\left(q_2^{\alpha}\right)-\gamma f(q_1)}$	$v_{2u} = \frac{(1-\delta)p_s+p_1}{(1-\gamma\delta)f(q_1)}$

Table 3.1: Marginal Customers

Buyers of the early version do not reinvest in the stable module if

[5]The results from this section are applicable to both proprietary and non-proprietary systems. To make the presentation simpler, I set the proprietariness penalty parameter$\beta = 1$ in this section.
While conditions are derived for products with installation costs, the analogous expressions for products with upgrade cost are derived similarly.

they decide to upgrade their systems when $\mathcal{I}_2$ is launched. Consequently, the market segment for which the option of buying $\mathcal{P}_1$ alone is ideal diminishes as the portion of investment in $\mathcal{S}$ relative to $\mathcal{I}_t$ grows. Segmentation patterns (SP) and corresponding participation constraints for different values of p_s are summarized in properties 3.3.1 and 3.3.2.

Property 3.3.1. Segmentation for Rapid Improvement $\delta f\left(q_2^\alpha\right) > f\left(q_1\right)$

Define

$$
\begin{aligned}
P_1 &= \frac{p_2 f\left(q_1\right)\left(1-\gamma\delta\right) - p_1\left(f\left(q_2^\alpha\right) - \gamma f\left(q_1\right)\right) - C_I F_I}{\left(1-\delta\right)\left(f\left(q_2\right) - \gamma f\left(q_1\right)\right)} \\
P_2 &= \frac{p_2 f\left(q_1\right) - p_1 f\left(q_2^\alpha\right) - C_I\left(f\left(q_2^\alpha\right) - f\left(q_1\right)\right)}{f\left(q_2\right) - f\left(q_1\right)}
\end{aligned}
$$

where $F_I = \left(f\left(q_2^\alpha\right) - f\left(q_1\right)\left(1+\gamma\left(1-\delta\right)\right)\right)$.

For all non-negative prices (p_1, p_2, p_s), *the market is divided according to one of the following segmentation patterns (SP) when the product is improving rapidly.*

SP 1. *If* $p_s \leq P_1$, *then* $\mathcal{D}_0 = [0, v_{01}]$; $\mathcal{D}_1 = [v_{01}, v_{1u}]$; $\mathcal{D}_2 = \emptyset$; $\mathcal{D}_u = [v_{1u}, 1]$

SP 2. *If* $P_1 \leq p_s \leq P_2$ *and* $p_1 + (1-\delta)\, p_s \leq (1-\gamma\delta)\, f\left(q_1\right)$, *then* $\mathcal{D}_0 = [0, v_{01}]$; $\mathcal{D}_1 = [v_{01}, v_{12}]$; $\mathcal{D}_2 = [v_{12}, v_{2u}]$; $\mathcal{D}_u = [v_{2u}, 1]$

SP 3. *If* $P_1 \leq p_s \leq P_2$ *and* $p_1 + (1-\delta)\, p_s > (1-\gamma\delta)\, f\left(q_1\right)$, *then* $\mathcal{D}_0 = [0, v_{01}]$; $\mathcal{D}_1 = [v_{01}, v_{12}]$; $\mathcal{D}_2 = [v_{12}, 1]$; $\mathcal{D}_u = \emptyset$

SP 4. *If* $P_2 \leq p_s$, *then* $\mathcal{D}_0 = [0, v_{02}]$; $\mathcal{D}_1 = [v_{02}, v_{2u}]$; $\mathcal{D}_2 = \emptyset$; $\mathcal{D}_u = [v_{2u}, 1]$

Proof. The proof is provided in the Appendix □

Property 3.3.2. Segmentation for Gradual Improvement $\delta f(q_2^\alpha) \leq f(q_1)$

For all non-negative prices (p_1, p_2, p_s)*, the market is divided according to one of the following segmentation patterns (SP) when the product is improving rapidly.*

SP 1. *If* $p_s \leq P_2$*, then* $\mathcal{D}_0 = [0, v_{01}]$*;* $\mathcal{D}_1 = [v_{01}, v_{1u}]$*;* $\mathcal{D}_2 = \emptyset$*;* $\mathcal{D}_u = [v_{1u}, 1]$

SP 2. *If* $P_2 \leq p_s \leq P_1$ *and* $p_2 \leq f(q_2^\alpha) - \gamma f(q_1)$*, then* $\mathcal{D}_0 = [0, v_{01}]$*;* $\mathcal{D}_1 = [v_{01}, v_{12}]$*;* $\mathcal{D}_2 = [v_{12}, v_{2u}]$*;* $\mathcal{D}_u = [v_{2u}, 1]$

SP 3. *If* $P_1 \leq p_s \leq P_2$ *and* $p_2 > f(q_2^\alpha) - \gamma f(q_1)$*, then* $\mathcal{D}_0 = [0, v_{01}]$*;* $\mathcal{D}_1 = [v_{01}, v_{12}]$*;* $\mathcal{D}_2 = [v_{12}, 1]$*;* $\mathcal{D}_u = \emptyset$

SP 4. *If* $P_2 \leq p_s$*, then* $\mathcal{D}_0 = [0, v_{02}]$*;* $\mathcal{D}_1 = [v_{02}, v_{2u}]$*;* $\mathcal{D}_2 = \emptyset$*;* $\mathcal{D}_u = [v_{2u}, 1]$

Proof. Similar to proof of Property 3.3.1. □

Property 3.3.1 provides some intuition about the effect of product modularity when the improvement is deemed rapid. Consider the effect of varying p_s for a given pair improving module prices p_1 and p_2, and suppose that p_1 and p_2 are within reasonable bounds[6]. When $p_s \leq P_1$, only a fraction of first period customers upgrade when $\mathcal{I}_2$ is available. However, if p_s is raised such that $p_s \geq P_2$, all first period customers upgrade their products. If the firm commits to an architecture with a higher stable module price relative to the overall costs of $\mathcal{P}_1$ and $\mathcal{P}_2$, customers can retain a significant part of their initial investment when they upgrade. This enables easier retention of the customer

[6]Note that when p_1 and p_2 are small, SP3 never obtains.

base as the firm moves along a path of rapid innovation. Firms involved in RSI face the problem of *balking* by customers, who temporarily or permanently stop upgrading their products till technological improvements become less turbulent. Dhebar (1996) suggests that producers should pace innovation to match customer ability to adopt; but it is clear that architectural choice can result in the same without slowing down the innovative effort.

3.3.2 Optimal Pricing for Modular Proprietary System (MP)

Special upgrade prices cannot be offered for integral products in markets where first period customers cannot distinguish themselves, but modular upgradability can be used in lieu of upgrade pricing even in these circumstances. Proposition 3.3.3 gives optimal prices when the firm has the ability to commit to a constant price, p_s. In proving it (Appendix), it is assumed that $c_1 = c_2 = c_s = 0$, but the validity of the main results has been tested numerically for several combinations of costs.

Proposition 3.3.3. Optimal Pricing for Modular Proprietary Systems *The optimal set of prices for the modules that result in a SP 1 sub-game perfect equilibrium are as follows:*

$$\begin{array}{ll} p_s^* = \frac{(1-\gamma\delta)f(\beta q_1)}{2(1-\delta)},\ p_1^* = 0,\ p_2^* = \frac{f\left(\beta q_2^\alpha\right)-\gamma f(\beta q_1)}{2} & \textit{for RSI} \\ p_s^* = \frac{f(\beta q_1)\left(f\left(\beta q_2^\alpha\right)-\gamma f(\beta q_1)\right)}{2\left(f\left(\beta q_2^\alpha\right)-f(\beta q_1)\right)},\ p_1^* = 0,\ p_2^* = \frac{f\left(\beta q_2^\alpha\right)-\gamma f(\beta q_1)}{2} & \textit{for GSI} \end{array}$$

The optimal set of prices for the modules that result in a SP 4 sub-game perfect *equilibrium are as follows:*

$$\begin{array}{ll} p_s^* = \frac{f(\beta q_1)}{2},\ p_1^* = 0,\ p_2^* = \frac{f\left(\beta q_2^{\alpha}\right) - f(\beta q_1)}{2} & for\ RSI \\ p_s^* = \frac{(1-\gamma\delta) f(\beta q_1)}{2(1-\delta)},\ p_1^* = 0,\ p_2^* = \frac{(1-\delta) f\left(\beta q_2^{\alpha}\right) - (1-\gamma\delta) f(\beta q_1)}{2} & for\ GSI \end{array}$$

These equilibriums are unique in pure-strategies.

Proof. The proof is in the Appendix. □

The optimal price for the stable module (p_s^*) is higher than that of the improving module. Higher p_s makes customer purchase decision easier since it leaves a smaller margin in the second period for the firm to price opportunistically. Further, when p_s is larger, customers are able to protect more of their prior investment when the product is upgraded. For all rates of innovation (t_d) and the product qualities, the profit maximizing strategy for the firm is to set the price of $\mathcal{S}$ at the upper bound dictated by the market participation constraint. Therefore, to induce the maximum number of customers to upgrade their products in a modular fashion, the firm subsidizes the first version of its improving module completely through sales of the stable module[7].

The stable module prices are non-increasing in γ, and therefore in learning rate r_L. To understand this, first note that all of the equilibriums identified in Proposition 3.3.3 are intertemporally discriminating, in which high-end customers buy $\mathcal{P}_1$ and upgrade to $\mathcal{P}_2$. These customers, whose preferences are critical in determining the optimal prices, view the first version mainly as a

[7]This result obtains even when nominal, non-zero production costs are included in the model.

non-durable good that will be used only for a single period. When learning-by-using contributes significantly to the perceived lifetime quality of a product, a larger portion of the benefits are delayed. Recall that the per period productivity of the product (of quality q) is given by $(1-\gamma\delta) f(q)$. As a result, the price high-end customers are willing to pay for the first version is lower, resulting in the inverse relationship between p_s^* and r_L for a given $f(q)$.

The relationship between second period price p_2^* and r_L, however, depends on the segmentation pattern chosen by the firm. In SP 1, the second version is sold exclusively to high-end upgraders who not only own the previous version, but have also accumulated expertise in using it. To induce them to overcome this acquired attachment to the old product, the firm is forced to discount the second version further. Therefore, p_2^* in non-increasing in r_L. To further understand the role of r_L, let us consider the special case where $r_L = 0$ ($\gamma = 1$).

Corollary 3.3.4. *When customers do not realize productivity gains by using a product, the optimal prices lead to a unique sub-game perfect equilibrium*

$$p_s^* = \frac{f(\beta q_1)}{2},\ p_1^* = 0,\ p_2^* = \frac{f(\beta q_2^\alpha) - f(\beta q_1)}{2}$$

First, the optimal prices are independent of the rate of improvement when learning effects are absent. This indicates that unlike the manufacturer of an integral product, the producer of such a modular upgradable system need not regulate the pace of innovation or place additional pricing constraints. However, the pricing policy shown above is not intertemporally discriminating.

By targeting the same set of customers with either version, the firm optimally skims the market at the same level in both periods. This result is consistent with previous observations on intertemporal discrimination (without innovation or customer learning). "The price cuts necessary to attract a wider market induce too many buyers to delay their purchases, making price discrimination unprofitable" (Stokey, 1979). Additionally, an attempt to be aggressive with the first product (in a proprietary architecture) results in turning away too many higher end customers of the improved product.

3.3.3 Optimal Pricing for Modular Non-proprietary Design (MN)

The point of modular upgradability is easy upgrading and investment protection; it removes the shadow of obsolescence from the users mind and, from a cost standpoint, it extends the depreciation time for the purchased equipment. But this point may not be conveyed successfully to customers unless they are convinced that the stable module price p_s will not be lowered later to take advantage of their first period purchase decisions. Making the stable module widely available as a separate retail item or an industry standard commodity could help address customer concerns. In this section, I focus on the use of non-proprietary modular product architectures as a vehicle to facilitate adoption of rapidly improving products.

Suppose a competitively supplied version of $\mathcal{S}$ is available. The firm sets prices p_1 and p_2, while the standard module is available in the market at a competitive price of p_s. Customers' investment in the stable module $\mathcal{S}$ is taken into consideration by the firm when prices for $\mathcal{I}_t$ are fixed. The optimal pricing policies for RSI are described in Proposition 3.3.5.

Proposition 3.3.5. Optimal Pricing for Non-Proprietary Systems under RSI

Under Rapid Sequential Innovation, the feasibility of any segmentation pattern and optimal prices depend on the price of the stable module p_s, as follows. A SP 1 sub-game perfect equilibrium can be achieved when $p_s < \frac{(1-\gamma\delta)f(q_1)}{2(1-\delta)}$. The optimal prices are

$$p_1^*(p_s) = \frac{(1-\gamma\delta)f(q_1)-2(1-\delta)p_s}{2},\ p_2^* = \frac{f\left(q_2^\alpha\right)-\gamma f(q_1)}{2}$$

A SP 4 sub-game perfect equilibrium can be achieved can be achieved under the following conditions. For each γ, δ and α, there exist ϕ_1, ϕ_2, ϕ_3 such that the optimal pricing strategies are

$$\begin{aligned} p_1^*(p_s) &= \begin{cases} \frac{(1-\gamma\delta)f(q_1)-(1-\delta)p_s}{2} & if\ \phi_3 \geq p_s \geq \phi_2 \\ \frac{f(q_1)\left(f\left(q_2^\alpha\right)+p_s\right)-2p_s f\left(q_2^\alpha\right)}{2\delta f\left(q_2^\alpha\right)} & if\ \phi_2 \geq p_s \geq \phi_1 \\ Do\ not\ launch\ first\ version & if\ \phi_1 \geq p_s \end{cases} \\ p_2^*(p_s) &= \frac{f\left(q_2^\alpha\right)-p_s}{2} \end{aligned}$$

Proof. The proof, along with expressions for ϕ_1, ϕ_2 and ϕ_3, is provided in the Appendix. □

As discussed in Section 3.3.1, the SP 1 purchase pattern corresponds to the case when the high-end customers buy in the first and second periods, while customers in the middle purchase only in the first period. When the cost of procuring the off-the-shelf module is sufficiently high, the first period offering is expensive, thus pushing the market toward delayed adoption ($p_s > (1-\gamma\delta) f(q_1) / 2(1-\delta)$). Therefore, it is not profitable to introduce the first version as the basic product intended for a wider customer base.

Only customers at the higher end of market are interested in the first period version in SP 4. They are motivated by not having to invest in $\mathcal{S}$ again at the point of upgrade. Therefore, a low p_s implies that the firm has to select a lower p_1 to launch $\mathcal{I}_1$ successfully. As a result, when $p_s \leq \phi_1$, the low price of the stable module makes launching $\mathcal{I}_1$ unprofitable. Therefore, the prices of the improving modules are non-increasing in p_s, indicating that adopting a costlier stable module results in reduced revenue per unit produced for the focal firm.

3.3.4 Pricing with Installation Costs

In this section, I extend the results from Sections 3.3.2 and 3.3.3 above to more general settings where customers incur either (i) a fixed cost C_I for installing each purchase under non-proprietary design, and (ii) a fixed C_U for disassembling and assembling when a modular proprietary system is upgraded. While C_I reduces the customer's net benefit from each version, C_U affects only customers that upgrade. These costs also increases the customer's resistance to upgrade when the better product is available. In Proposition 3.3.6 below, the equilibrium prices charged by the firm when costs incurred by customers are considered.

Proposition 3.3.6. Modular Proprietary Systems with Upgrade Cost *The SP1 equilibrium is achievable when $C_U \leq \omega_1^U$. The optimal prices that result in a sub-game perfect equilibrium are as follows:*

$$p_s^* = \frac{(1-\gamma\delta)f(\beta q_1)}{2(1-\delta)} - C_U \frac{2\delta f\left(\beta q_2^\alpha\right) - f(\beta q_1)(1+\gamma\delta)}{2(1-\delta)\left(f\left(\beta q_2^\alpha\right) - \gamma f(\beta q_1)\right)},\ p_1^* = 0,\ p_2^* = \frac{f\left(\beta q_2^\alpha\right) - \gamma f(\beta q_1)}{2} - \frac{C_U}{2}$$

The SP4 equilibrium is achievable when $C_U \leq \omega_4^U$. The optimal prices that result in a sub-game perfect equilibrium are as follows:

$$p_s^* = \frac{f(\beta q_1)}{2},\ p_1^* = 0,\ p_2^* = \frac{f\left(\beta q_2^\alpha\right) - f(\beta q_1)}{2f\left(\beta q_2^\alpha\right)}$$

where $\omega_1^U = \frac{(1-\gamma\delta)f(\beta q_1)}{2\delta f\left(\beta q_2^\alpha\right) - (1+\gamma\delta)f(\beta q_1)}$ *and* $\omega_4^U = (1-\gamma\delta)\, f\left(\beta q_1\right)/\delta$.

Proof. Similar to the proof of Proposition 3.3.3 □

Note that it is profitable to offer modular upgradability only when the upgrading cost C_U is less than ω_i^U. Naturally, prohibitively high costs of upgrading dissuade customers from exercising this option provided through product design, *even* when the producer packages the modules together for new buyers. When the stable module is non-proprietary, firms seldom offer packaged products to consumers. In Proposition 3.3.7 below, optimal prices when installation is performed by customers in each period are derived. While third-party providers may offer the service of integration, a cost is incurred in obtaining this service. Therefore, I do not consider upgrading costs separately.

Proposition 3.3.7. Modular Non-Proprietary Systems with Installation Costs.

The SP 1 sub-game perfect equilibrium can be achieved when $C_I \leq \omega_1^I$. *The optimal prices are*

$$p_1^*\left(p_s\right) = \frac{(1-\gamma\delta) f(q_1) - 2(1-\delta) p_s}{2} - C_I \frac{2f\left(q_2^\alpha\right) - f(q_1)(1+\gamma(2-\delta))}{}, \; p_2^* = \frac{f\left(q_2^\alpha\right) - \gamma f(q_1) - C_I}{2}$$

A SP 4 sub-game perfect equilibrium can be achieved when $C_I \leq \omega_4^I$. *For each* γ, δ, α *and* C_I, *there exist* ϕ_1^I, ϕ_2^I, *and* ϕ_3^I *such that*

$$\begin{aligned} p_1^*\left(p_s\right) &= \begin{cases} \frac{(1-\gamma\delta) f(q_1) - (1-\delta) p_s}{2} - \frac{C_I}{2} & if\ \phi_3^I \geq p_s \geq \phi_2^I \\ \frac{f(q_1)\left(f\left(q_2^\alpha\right) + p_s\right) - 2 p_s f\left(q_2^\alpha\right) - C_I\left(2f\left(q_2^\alpha\right) - f(q_1)\right)}{2\delta f\left(q_2^\alpha\right)} & if\ \phi_2^I \geq p_s \geq \phi_1^I \\ \text{Do not launch first version} & if\ \phi_1^I \geq p_s \end{cases} \\ p_2^*\left(p_s\right) &= \frac{f\left(q_2^\alpha\right) - p_s - C_I}{2} \end{aligned}$$

where $\omega_1^I = \frac{f(q_1)(1-\gamma\delta) - 2p_s(1-\delta)}{2\left(f\left(q_2^\alpha\right) - f(q_1)(1+\gamma(1-\delta))\right)}$, $\omega_4^I = (2\delta\gamma - 1)\, f\left(q_2^\alpha\right)$
and $\phi_1^I = \frac{f(q_1)(1-\gamma\delta) - C_I}{1-\delta}$, $\phi_2^I = \frac{\gamma\delta f(q_1) f\left(q_2^\alpha\right) - C_I\left(f\left(q_2^\alpha\right) - f(q_1)\right)}{(1+\delta) f\left(q_2^\alpha\right) - f(q_1)}$
and $\phi_3^I = \frac{f(q_1)\left(f\left(q_2^\alpha\right)(2\gamma\delta - 1) - C_I\right)}{2\delta f\left(q_2^\alpha\right) - f(q_1)}$

Proof. Similar to the proof of Proposition 3.3.5 □

The prices charged by the firm for either product, and therefore the profits, decrease with C_I and C_U. Further the profits vanish when installation and upgrade costs exceed certain thresholds. This is due to the natural downward pressure that installation costs exert on a customer's willingness to buy or upgrade a product. Industrial customers typically enjoy the services of maintenance crews for testing and calibrating new machines, which lowers the installation cost relative to product quality. However, consumers who buy gadgets for personal use often find the effort and frustration associated with installation and upgrading costly relative to the utility derived. Firms that cater consumer markets might prefer to side-step complication installation instructions by assembling the gadgets before selling them. In that regard, the results from Propositions 3.3.6 and 3.3.7 offer an explanation for the skewed prevalence of modular upgradability primarily in industrial products.

While the results in this Section are derived assuming that the same cost is incurred equally by new and upgrading customers, the results easily extend to the case in which new installations and modular upgrades require different effort levels. This case is not presented since the more complicated expressions add little value to the discussion.

3.4. Optimal Architectures and Innovation Rate

In this section, the profitabilities of the different product design approaches are compared to determine the conditions under which the modular architectures yield higher profit. The innovation rate is then treated as a decision variable to examine how the optimal innovation rates compare under the modular and integral architectures.

3.4.1 Appropriateness of Different Architectures

A comparison of the profitability of the different product design approaches indicates that under fairly general conditions, the modular design and pricing approaches yield profits superior to the integral design choices. Here different architectures are compared for a pre-specified launch time t_d.

Let the optimal profits from the integral architecture, the modular proprietary architecture, and the modular non-proprietary architecture be π_{IN}, π_{MP}, and $\pi_{MN}(p_s)$ respectively. It is assumed that the integral product can be sold in the RSI case with a guarantee that special upgrade prices will not be offered later (which is optimal for the integral architecture). The architectural choices can be ordered with respect to the efficiency they allow in price discrimination when there are no adverse effects of modularity ($\alpha = 0$) and when there are no technological disadvantages in adopting proprietary solutions ($\beta = 1$).

Proposition 3.4.1. *When $\alpha = 0$ and $\beta = 1$, the profits are ordered as follows:*
1. The modular proprietary architecture results in a higher profit than the integral architecture

$$\pi_{MP} > \pi_{IN} \ \forall\ \delta < 1,\ \gamma \geq 1,\ \gamma\delta < 1$$

2. For all levels of stable module prices, the modular proprietary approach is more profitable than the non-proprietary approach

$$\pi_{MP} > \pi_{MN}\left(p_s\right)\ \forall\ p_s > 0$$

Proof. The proof is in the Appendix. □

The first part of the proposition, which presents the dominance of modular proprietary architecture over the integral architecture, is driven by the additional pricing flexibility of setting p_s in the modular proprietary solution

(π_{MP}). Also, when product quality is not impacted due to proprietary architecture, the firm's profit with the non-proprietary architecture ($\pi_{MN}(p_s)$) is lower than that of the proprietary modular architecture (π_{MP}) because the firm does not earn revenues from the stable module (p_s goes to the firm manufacturing $\mathcal{S}$).

Now, the design choices for different levels of r and α, which capture the customer patience (δ) and any adverse impact of modularization on product quality, are compared. Fig 3.3 shows the dominant architectural choice for different combinations of α and δ. In region *INT*, the integral design solution is most profitable, while in regions *MP* and *MN*, the proprietary and non-proprietary modular solutions are optimal.

Since α is a direct measure of the loss of product quality that occurs due to modularization, a high α represents a greater implicit cost of designing a modular product. Therefore, for any customer discounting factor δ, modular solutions, proprietary and non-proprietary, are more attractive than the no-upgrade pricing approach for lower levels of α. Since our primary interest is in the efficacy of modular upgradability in managing rapid sequential innovation, combinations of α and δ that lead to an artificial throttling of innovation are excluded[8].

When the firm has the option of selecting between a proprietary and non-proprietary approach, customers' ability to leverage any investment in the

[8]In other words, Figures 3.3 and 3.4 are restricted to parameters that satisfy the condition $\delta f\left(\beta q_2^{\alpha}\right) > f\left(\beta q_1\right)$.

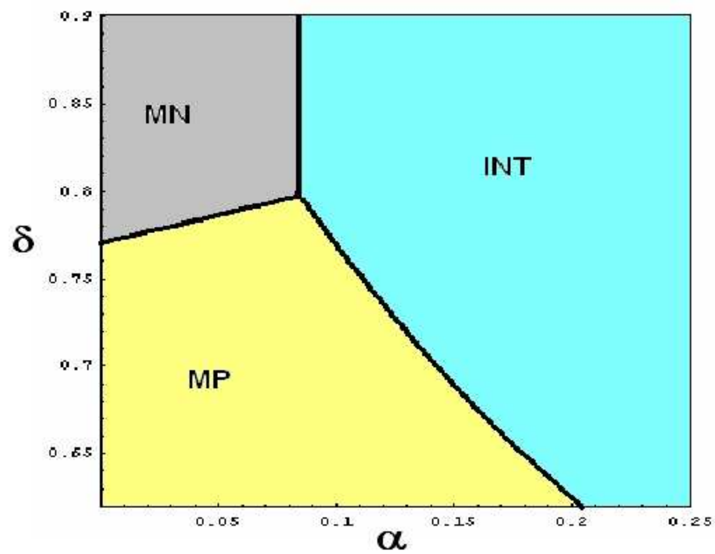


Figure 3.3: Dominant Architectures for $q_1 = 1$, $q_2 = 3$, $p_s = 0.1$, $\beta = 0.85$ and $\gamma = 1$

stable module $\mathcal{S}$ becomes more important. When the inter-version duration t_d is longer, the present value of the improved version is reduced. This makes customers less willing to plan for upgrades when the new product is launched. The firm can overcome this resistance by allowing the customers to transfer a larger portion of their earlier investment. Recall that the stable module prices offered through the modular proprietary architecture allow the customers to transfer all of their investment to future upgrades. Further, when t_d is higher, the firm's discounted valuation of its own second period revenues is lower; this lowers the real cost of offering larger upgrade discounts (implicitly, through p_s) in the second period. As a result of these two forces, the firm finds it optimal to offer the proprietary modular architecture for smaller values of δ.

The influence of β can be understood using the example in Figure 3.4, which shows the variation of architectural decisions between two levels of β. A higher value of β denotes a lower disparity between the firm's ability and the industry standard in producing $\mathcal{S}$ or a greater level of acceptance of proprietary products. When the firm is more competitive, i.e. when $\beta = 0.875$, the non-proprietary solution is dominant in region *MN*, the proprietary modular solution should be adopted in regions *MP* and *B*, and a non-modular product should be sold in all other regions. When β falls to 0.85, the non-proprietary modular architecture is the best alternative for the firm in regions *MN, A* and *B*. The integral system is profitable only in region *INT*. As β approaches 1, the non-proprietary solution is not used under any condition. The non-proprietary approach becomes the ideal choice as β approaches 0.

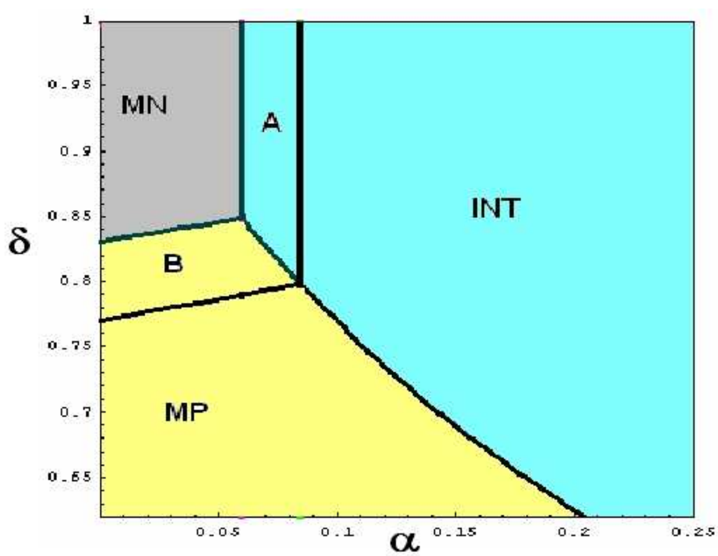


Figure 3.4: Dominant Architectures for $q_1 = 1$, $q_2 = 3$, $\delta_f = 0.6$, $p_s = 0.1$, $\beta = 0.85$ or 0.875, $\gamma = 1$

As discussed in Section 3.3.4, the additional benefits customers derive from modular upgradability come at the loss of installation and upgrading services previously performed by the firm itself. Naturally, if the interfaces connecting the modules are complex, these costs are larger and customers are more willing to select one of the versions. In Figure 3.5, as C_I increases, the non-proprietary solution is less profitable than both modular proprietary and integrated designs. Similarly, a larger C_U decreases the attractiveness of the modular proprietary alternative. While these results suggest that modular architectures are perhaps more conducive to certain market and technological environments than others, they also reveal the importance of designing for easy upgradability.

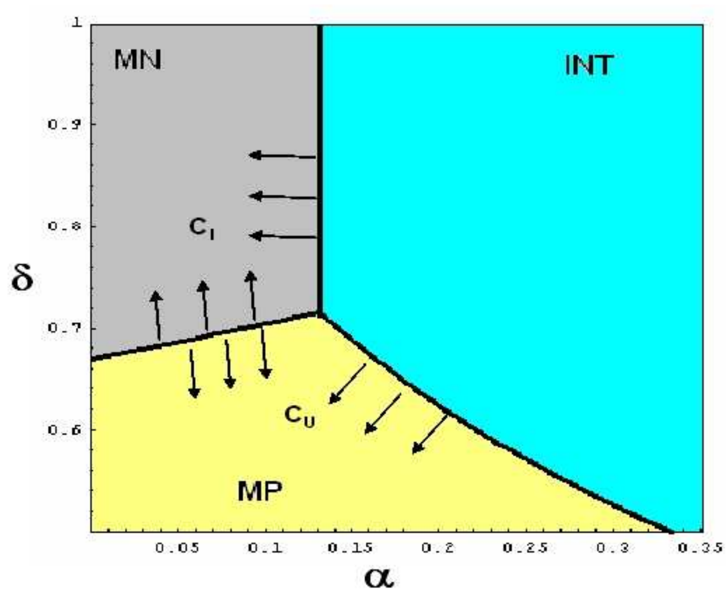


Figure 3.5: Dominant Architectures for $q_1 = 1$, $q_2 = 3$, $\delta_f = .6$, $p_s = .1$, $\beta = .85$, $\gamma = 1$, $C_I = .05$, $C_U = .01$

These results show that the firm might have strong reasons to pursue a non-proprietary architecture (outsourced stable module) in spite of the reduced revenues it obtains from the sales of each stable module unit. The intuition that the non-proprietary solution is more preferable when customers are wary of proprietary approaches or the firm is less capable in designing the stable module (low β) is indeed confirmed. However, the influence of the customer's discount factor on the choice of the type of modular architecture is quite subtle, and goes to the very core of the benefits of modular upgradability for rapidly improving products. Whereas these results hold when the discount factors of the firm and its customers are correlated through t_d in industrial markets, the results can be different in consumer markets where the firm and individual consumers could differ in their relative patience to receive future benefits. This is discussed in Appendix A.1.

3.4.2 Optimal Innovation Rates

In the previous sections, the optimal design architecture and pricing at a given rate of innovation were identified (with $\delta(t_d)$ representing the innovation rate). I now endogenize the innovation rate and treat the inter-version time t_d as a decision variable to study the impact of architecture on the optimal rate of innovation (while addressing customer regret and maximizing firm profit). Specifically, the demand-driven optimal innovation rate t_d^* for the modular proprietary, non-proprietary and integral architectures are compared[9].

Deriving optimal innovation rates requires a model of development cost, and ours is based on the assumption that a specific set of resources will be dedicated to the product development effort. Prior studies have shown that there are diminishing returns to resource investment in product development (Graves, 1989). To develop a product that delivers performance $f(q_2)$ from the technology with potential q_2, I model that the firm incurs a cost that depends on the development time t_d, and the qualities of the early and improved versions, q_1 and q_2. The profit expressions in earlier sections are expressed in terms of δ, which is bounded between 0 and 1; so it is convenient to express the functional form with respect to $\delta(t_d)$. The development cost is modeled to be:

$$C\left(t_d, q_1, q_2\right) \doteq C_d\left(q_1, q_2\right) g\left(\delta\left(t_d\right)\right)$$

where $g(0) = \infty,\ g(1) = 0,\ g'(.) > 0$ and $g''(.) > 0$.

Integral and Modular Proprietary Architectures

First, I compare the optimal rates of innovation under Modular Proprietary and Integral architectures. For any given inter-version time t_d, the optimal prices set by the firm for each design choice is given by Propositions

[9] To make the presentation simpler, I assume that the per-period learning rate $\gamma\left(t_d\right)$ is independent of t_d and ignore costs incurred by customers. Incorporating $L > 0$, subject to the assumption that $L < r$ does not change the main results of this section.

3.3.3 and 3.3.5 above. The corresponding profits can be derived from Equations 3.5 and 3.7 in Section 3.2.2. The firm's total profit using the proprietary modular architecture as a function of the rate of innovation, t_d, is:

$$\Pi_{MP}(t_d) = \frac{f(\beta q_1)}{4} + \delta(t_d)\frac{f(\beta q_2^{\alpha}) - f(\beta q_1)}{4} - C_d(q_1, q_2)g(\delta(t_d)) \tag{3.8}$$

Similarly, for the integral architecture, the profit is:

$$\Pi_{IN}(t_d) = \begin{cases} \frac{(1-\delta(t_d))f(\beta q_1)}{2} + \delta\left(t_d\right)R_2 - C\left(t_d, q_1, q_2\right) & \text{if } \delta(t_d)f(\beta q_2) \leq f(\beta q_1) \\ \frac{(1-\delta(t_d)^2)f(\beta q_1)}{4} + \delta\left(t_d\right)R_2 - C\left(t_d, q_1, q_2\right) & \text{if } \delta(t_d)f(\beta q_2) > f(\beta q_1) \end{cases}$$

where $R_2 = \frac{(f(\beta q_2) - f(\beta q_1))}{4}$.To obtain some basic insights, I compare the innovation rates for the proprietary modular and integral architectures when $\beta = 1$ and $\alpha = 0$. No specific functional forms are required for comparing innovation rates under the two alternatives. When the firm's own modules are not inferior to the industry standards, and when there are no negative consequences of modularity, the firm has an incentive to innovate faster if it adopts a modular architecture for the system.

Proposition 3.4.2. Innovation under Modular and Integral Architectures

When there are no quality losses due to modularization ($\alpha = 0$), modular proprietary architecture allows for a faster rate of innovation than an integral architecture without causing customer regret.

$$t_d^{MP*} \leq t_d^{IN*}$$

The above result that a modular design choice allows for faster optimal demand-driven innovation (even when any supply-side efficiencies involved in modular design are not considered) is, to the best of my knowledge a new insight not found in the existing literature. The reason for faster optimal innovation rate under the modular architecture can again be traced back to the additional degree of freedom in pricing this design provides. More pricing freedom results in an increased ability to leverage investments in innovation, thus tilting the tradeoff in the favor of increased development effort.

Modular Proprietary and Non-Proprietary Architectures

When the price of the market-sourced stable module p_s is low (close to 0), the Modular Non-proprietary approach is similar to having an integral architecture because the role of the stable module is insignificant. Therefore, the Modular Proprietary architecture results in faster innovation. On the other extreme, if the stable module is a valuable component of the product (high p_s), the firm again does not benefit much from innovation as a significant portion of the sales goes to the vendor of the stable module. This again leads to faster innovation under Modular Proprietary approach. These observations are captured in the following Proposition.

Proposition 3.4.3. Innovation Rates under Proprietary and Non-Proprietary Architectures

The optimal rate of innovation under the Modular Proprietary Design exceeds the rate of innovation under the Non-Proprietary design both for high and low *prices of the stable module.*

Proof. The proof (in the Appendix) offers bounds for the stable module prices above and below which the Proprietary approach leads to faster innovation. □

Interestingly, for intermediate values of p_s, the optimal innovation rate under Modular Non-proprietary approach *could* exceed the innovation rate for the Proprietary architecture. Note that a higher price p_s restricts the profitability of both first and second period sales. When the stable module is moderately expensive, under the non-proprietary approach, p_s has a stronger constraining effect on first period prices. The firm, which is now relatively less sensitive to first period profits, makes an unencumbered decision to maximize discounted second period profits resulting in higher innovation rate under the non-proprietary architecture.

3.5. Conclusions

Driven by feedback from their investment-conscious customers, firms have begun offering an easier upgrading path using upgradable modules, a trend increasingly seen in industrial markets. I have attempted to formalize and analyze modular upgradability for sequentially improving products that yield customer productivity improvements. The results provide a nuanced understanding of the role of a product's modular design in segmenting customers in a heterogeneous market when costs may be incurred in installing and upgrading modular products. Localizing product improvements and developing the product to be upgradable in modules ensures that initial investment by customers is not completely obsoleted by subsequent introduction of superior products, often outweighing any additional costs associated with modularity. Consequently, the seller profits more by leveraging the increased pricing freedom to segment customers without restraining the pace of innovation. Furthermore, modular designs are also more conducive to a faster launch of improved versions - while prior research in Operations offers a resource-based motivation for modularity, this research offers an alternative explanation for faster innovation in modular products from a market-adoption perspective (Section 3.4.2).

One of the central contributions in this research are the first order insights that were derived about the connection between product architecture and market segmentation, which are typically analyzed in mutual isolation. With respect to the existing literature, two additional degrees of freedom have been added, which include product architecture and introduction timing to help firms manage sequential innovation. Contrary to the suggestion that using industry standard components can be debilitating to the product line in the long run (Morris and Ferguson, 1993), using non-proprietary components might indeed be an attractive option to realize the modular approach. In fact, there is a strong incentive to use standard subsystems when cost-side advantages of standard components are factored in. Whereas the understanding in previous research is that firms might indulge in *open-sourcing* to encourage other firms to participate in innovation (Garud and Kumaraswamy, 1993), adopting standard solutions for some modules can help firms achieve inter-temporal discrimination (section 3.3.3). Further, this analysis confirmed that the incentive for modularization and maintenance of proprietary control are dependent on design effects, product characteristics like the learning rate and market characteristics such as firm discount rates. When the direct or opportunity costs of modularization and proprietariness are high, non-proprietary or integral architectures may indeed be preferable.

The implication of this work for innovating firms going forward is that modular upgradable product design, introduction timing, and coordinated pricing can be valuable instruments for firms to manage the market launch of rapidly improving products. By identifying regions of appropriateness of the different approaches to upgrading the product in modules, it is possible to identify factors that a firm must recognize and influence in designing improving products. We learned exactly how installation and upgrade costs (C_I, C_U) make modular designs less valuable for the customers as well as the firm. In consumer products, even more than industrial products, these costs tend to be larger relative to the utilities derived from the products. While this result is consistent with the observation that modular designs are currently more prevalent in industrial sectors, it provides some basic guidance on pairing technologies and markets through product design. An emphasis on performance attributes alone often leads to complex product designs, and dense and intricate interfaces between functional modules (Simon, 1969). In order to commercialize rapidly improving sequences of products, a firm should consider *designing its products for upgradability.* In addition to functional modularity and localization of improvements, products designed for upgradability will also enable customers to disassemble and quickly re-install the constituents of a product in an effortless manner.

In these first steps in understanding how architecture influences market segmentation, some stylized assumptions were necessary. The long-run viability of product architectures needs to be addressed in the future by going beyond a two-period model. Selling a proprietary modular product results in an equilibrium with the same set of buyers in all periods; although it is successful in a 2-period model, this can lead to a stationary customer base, performance saturation (Krishnan and Zhu, 2006), and increased competition. The single product, replacement model considered in this chapter is in accordance with the body of work on rapid sequential innovation. In a more general replacement setup, Stokey (1988) suggests that periodic addition (deletion) of high (low) quality products results from industry-wide spillovers of learning experiences. It has also been assumed that there is no resale market for such rapidly improving products. Although this can be enforced by the manufacturer for some goods, presence of second hand markets can moderate the effects of monopolistic opportunism considered in this chapter.

The results presented here are derived under the stylized supposition that production costs are negligible, however, numerical analysis shows that the fundamental results indeed continue to hold when production costs are considered. When marginal costs are negligible, and when modularization degrades product quality, offering trade-ins and buy-backs may, in fact, be more profitable than opting for modular upgradeable designs. However, trade-in alternatives entail distribution, reverse logistics and disposal costs that could make them expensive for some products. Further, the customer's lower incentive to maintain stable modules that will be returned through the trade-in creates undesirable moral hazard issues. The discussion is focused on durable products such as industrial assembly systems which cannot be bought back without considerable risk for the firm and expense for the customer.

The insights generated here offer a new and previously unknown rationale for modularizing the architecture in the context of rapid sequential innovation. The results also help decide when to use a proprietary modular architecture versus using an open systems approach. The application of these ideas can help ensure that rapid improvements can be realized without discouraging customers from purchasing these products, thereby stimulating market growth and profits for firms.

Chapter 4

Sequential Innovation with Strategic Consumers and Suppliers: Time Inconsistency with Integrated Product Design and Pricing

4.1. Introduction

Advances in sciences and engineering result in significant increases in technological capabilities of products. These improvements often lead to rapid obsolescence of earlier products purchased by consumers. One approach to induce apprehensive consumers to buy improving products is for the seller to design the product in a modular upgradable fashion. By partitioning these products into subsystems, which is termed as *modular sequential innovation*, the seller allows customers to upgrade only the improving modules and preserve some of their investments in the stabler modules over an extended period of time (Ramachandran and Krishnan, 2007). Modular sequential innovation has been embraced by many firms recently: In the semiconductor photo-lithography equipment segment, industrial customers such as Intel and AMD are able to upgrade their systems in a modular fashion by buying from firms such as ASM Lithography (Chuma and Aoshima, 2003; Dutch News Digest, 2003). Firms such as IBM and Rackable systems in the computer server industry, and Vi-Technology in the optical inspection market, have also designed their products in a modular upgradable fashion (The News & Observer, 2006).

However, modular sequential innovation - though increasingly common in industrial products - is relatively less common in consumer technology markets. Sellers in consumer markets cannot commit to specific architectures and pricing policies for products that would become available in the future. Consequently, strategic consumers might be able to predict the seller's incentive to integrate the improved product or price the modules such that the advantages of modular upgradability are diminished. This creates a time-inconsistency problem for the seller with respect to the design and pricing of improved versions. In this chapter, I consider the impact of strategic consumers on how sequentially improving products are designed, sourced and priced. Although several papers have previously considered the role of strategic consumers in determining operating policies (see Su, 2006 for a recent review), the impact of such foresightedness on product design itself has not been studied.

In addition to the design architecture (modular or integrated), the fashion in which the stable module is sourced also affects the interactions between the consumer and the seller. I consider three sourcing strategies in the chapter: (i) Internal sourcing with in-house production, (ii) Open sourcing from a consortium, and (iii) Specialist sourcing from a predetermined supplier. Each of these strategies - in addition to the different pricing freedoms they afford the seller - also engenders a unique set of constraints for the seller. These pricing constraints are necessary for the seller to overcome the time-inconsistency problem created by consumer foresight into its design incentives. Furthermore, under specialist-sourcing, the supplier of the stable module might behave strategically to appropriate some of the surplus created by the seller's innovation. This further exacerbates the time-inconsistency problem faced by the seller.

One of the central findings of this work is that inconsistency in the seller's incentives might make it impossible to pursue certain approaches to inter-temporal market segmentation for products that are sequentially obsolesced by technological innovations. I formally characterize the coordinated decision approach to product design, sourcing and pricing that is required to introduce modularly improving products. The results in this work show that it is possible to commit to future product designs even in when the firm's design incentives are temporally inconsistent, but this takes integrated product design, pricing, and market segmentation.

The consideration of investments made by the seller in developing the improving module adds further nuance to our understanding of sequential innovation. While the issue of product obsolescence weighs more heavily on the minds of consumers when the product improves rapidly, rapid sequential innovation might turn out to be quite valuable for the seller. In particular, when the seller depends on a strategic supplier of the stable module, a greater improvement of the improving module limits the supplier's room to behave opportunistically. Therefore, in contrast to open-sourcing, the seller's investment in the improving-module under specialist-sourcing is higher when the stable module is of a higher quality. This subtle difference, heretofore unknown to the best of my knowledge, underscores how sourcing, design and development strategies are intertwined in the case of modular sequential innovations.

The rest of the chapter is organized as follows. I define some key constructs and formalize the problems associated with the commercialization of modular, sequentially improving technologies § 4.2. The proposed solutions are discussed in § 4.3, followed by the analysis of interactions with a specialist stable module provider in § 4.4.

4.2. Modular Sequential Innovation: Model Formulation

A model of sequentially improving products, each one of which is launched by a seller as a combination of modular subsystems, is developed in this section. The model assumptions are stated first, followed by a discussion of the timing of nature and decisions made by the seller and the consumers in the market, and define key constructs regarding the consistency of the seller's product design incentives over time.

4.2.1 Model: Assumptions, Decisions and Timing

Technology and Product Design. Consider the sequential two-period product introduction problem faced by the seller whose product is based on an improving *core* technology, which the seller has exclusive access to. The product offered in each period may be designed as one integral unit or architected as a system of two functional modules: an *improving* module into which the core technology of quality q_{tc} ($t \in \{1,2\}$) is incorporated, and a *stable* module of quality q_s that does not undergo substantial quality changes over time[1].

The maximum attainable quality, q_t, of version t, of the product depends on the qualities of the individual modules and the product design architecture. The seller makes the architecture selection independently for each version of the product, which is denoted by A_t, where $t \in \{1,2\}$ and $A_t \in \{\text{I, M}\}$, the integral (I) and modular (M) design architecture choices. It has been documented in the literature that modularizing a product's architecture can compromise its functional quality (for instance Ulrich and Ellison (1999)). This quality loss associated with modularization is captured through the parameter m ($0 \leq m \leq 1$). Here, a higher value of m indicates that the product can be designed as separable modules without affecting the quality to a large extent. This is reflected in the difference between corresponding qualities of integrated and modular products based on the same core technology: $\partial \left(q_t^I - q_t^M\right) / \partial m < 0$, where the superscript (I or M) refers to the selected product architecture.

The relative contribution of the improving module towards overall product performance is indicated by the parameter α. To ensure non-trivial solutions, it is assumed that $\partial q_t / \partial q_{tc}$ is positive and increasing in parameter α. In this chapter, a linear, additive functional form is used to capture the impact

[1] I initially focus on the seller's role in commercializing the core technology. The seller's role in developing the technology itself is considered subsequently.

of these different variables on product quality. The quality of the modular product is given by Equation 4.1.

$$q_t^M \doteq \alpha q_{tc} + m\left(1-\alpha\right) q_s \tag{4.1}$$

When m is higher, the product is inherently more integrated (less modular) and the modularization affects the product's quality to a lesser extent. For a completely integral product, quality is given by

$$q_t^I \doteq \alpha q_{tc} + \left(1-\alpha\right) q_s \tag{4.2}$$

Such an additive relationship between product quality and component qualities is similar to models used by other researchers like Ulku and Schmidt (2005) in operations and several others in marketing (see Carroll and Green (1995)). The robustness of this functional form has been tested for other model specifications as well, and almost all of the results and insights generalize to all where settings where the improvement in total quality is monotone decreasing in m.

The qualities of the improving modules depend on the underlying technology's improvement as well as on the investment made by the firm in development. I initially assume that the improving module's evolution is exogenous, but consider the firm's investment in product development in § 4.5. The technology behind the stable module does not improve over time, and the firm is capable of designing a stable module internally, if it needs to.

Sourcing and Pricing Decisions. The firm's design choice determines not only the qualities of the products offered, but also the different ways in which the firm could allow consumers to obtain the stable module - referred to as the *sourcing* decision. The sourcing decision in turn determines how the different modules are priced in each period and what external strategic interactions the firm must deal with. When the product is sold as an integrated unit, the firm produces both modules of the product in-house and makes the improving parts of the product incompatible with outside stable modules. However, the firm has several options with respect to sourcing the stable subsystem for a modular architecture. I consider three different sourcing options for the stable subsystem: (i) Internal sourcing, wherein the firm itself manufactures and sells the stable module, (ii) Open-sourcing, in which the firm makes architectural details publicly available for several other firms to develop compatible stable modules, and (iii) Specialist-sourcing, where the firm selects a specialist supplier as the sole provider of the stable module.

To cover the various sourcing and pricing decisions, let us consider the most general of the three cases above: specialist-sourcing for modular design (Figure 4.1). The seller sets prices p_t for version t of the improving module. Improvement in the core technology provides the seller the opportunity to offer different products (or combinations of products) to different consumers depending on their willingness to pay for product performance. As the seller cannot identify individual consumers' preferences for quality, it must select a price schedule $\{p_1, p_2\}$ such that in each of the two periods consumers self-select the product(s) intended for each of their types. The seller may also offer a discounted upgrade price p_2^u for consumers who upgrade their existing products. The specialist provider sets prices, p_{s1} and p_{s2}, for the stable module. Since the option of using an internally developed stable module is available, the improving module manufacturer might be able to influence the prices at which the stable module is offered. This influence of the strategic supplier is characterized using a simple Nash-Bargaining framework (Fudenberg and Tirole, 1991).

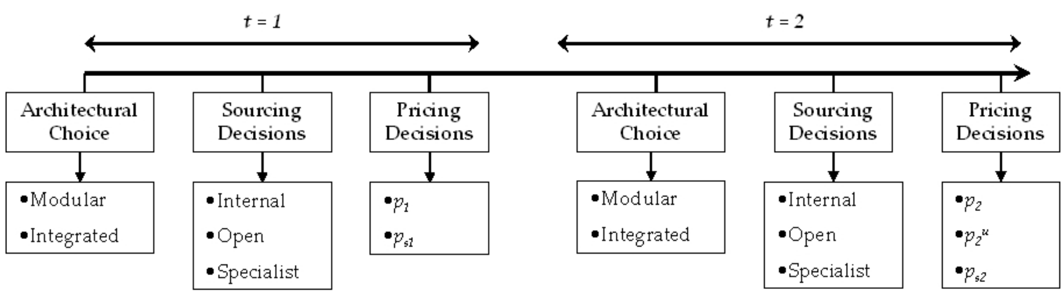


Figure 4.1: Timing of Seller's Decisions under Specialist-Sourcing

In open-sourcing, the manufacturer focuses on developing the improving module, and allows consumers to purchase any compatible stable module off-the-shelf, which will be competitively and directly supplied to consumers at a price p_s in the first period. Prices of such commoditized components may drop over time because of learning effects and improvements in production processes. Further, entry of more sellers in the market for the stable module may also lead to a reduction in the module's price over time. These reductions are predictable, and that the stable module's price falls to θp_s in the second period ($0 < \theta \leq 1$). The production cost of the stable module depends on the complexity of the module, and this is reflected in the market price as $p_s = kq_s$ $(k > 0)$. The open-sourcing case is a simplified form of the specialist-sourcing case in which $p_{s1} = p_s$ and $p_{s2} = \theta p_s$.

Internal sourcing might lead to lower product quality, but allows the firm to price both modules individually and independently, i.e. the firm sets p_{st} in addition to p_t. However, this additional pricing freedom also implies that the firm can fully price discriminate between new consumers and upgraders. Consequently, the pricing problem of the firm that internally sources the stable module is not unlike that of a firm that can individually identify new and repeat buyers. Since internal sourcing - by allowing the firm to vary the price of the stable module over time - leads to consumer regret (Dhebar, 1994), open- or specialist-sourcing serve as valuable alternative design strategies.

When the product is integrated in design, the stable module - designed by the firm - does not exist as a separate entity in the market. This situation is captured as a special instance of the specialist-sourcing scenario with $p_{s1} = p_{s2} = 0$ and $\alpha = 1$. Since the focus is on the potential deficiencies of modular sequential innovation, this design choice is summarily analyzed in Appendix B.0.2.

The Market. The market consists of customers distributed uniformly between 0 and 1 in v, their willingness to pay for performance. The utility that a consumer of type v derives from a product of quality q is given by a simple linear utility function in Equation 4.3. If the customer already has a product of quality $\hat{q}$, then the willingness to pay is assumed to be $v\,(q - \hat{q})$. Further, the seller and consumers discount future benefits from consumption and revenue by the per period discount factor δ. For clarity of exposition, a perfect capital market is considered, but the results generally hold when the seller and consumers discount future benefits at different rates.

$$W(q, v) = vq \tag{4.3}$$

Rapid innovation involves significant sequential improvement in product quality not only in absolute terms, but also in discounted terms ($\delta q_2 > q_1$). As a result, early versions are inadequate surrogates for advanced products launched later. While the model and results are general to both rapid and moderately paced sequential innovations, design-based market segmentation is particularly effective in rapidly advancing product categories. Under sequential innovation of technology-driven products, the effects of adverse attribute selection on the seller's profits far outweigh the effects of competition from used goods. In order to focus on the interaction between product architecture and commitment related issues in sequential innovation in-depth, the effect of second-hand markets are not included in this chapter. This assumption is also similar to those made in other papers on the intertemporal effects of sequential innovation (Dhebar, 1994; Kornish, 2001).

Consumption Decisions. Consumers have four choices in the model - they can buy either the first or second version, both versions or neither. Note that when the product is available in a modular upgradable form, a consumer who purchases both versions will continue to use the stable module bought in the first period with the new and improved module in the second period. The net utility obtained by a consumer of type v from each of the four actions is represented in the decision tree in Figure 4.2 - only the specialist-sourcing case is presented since other utilities are obtained through suitable simplifications. Each consumer selects the option that maximizes his or her net utility.

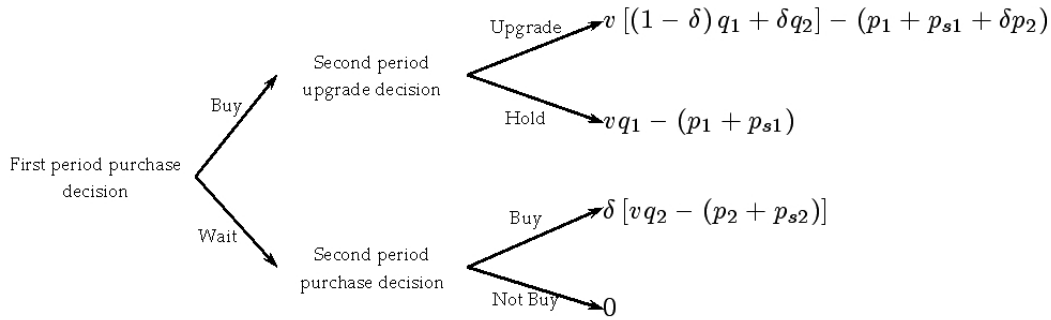


Figure 4.2: Consumer's Decision Tree under Specialist-Sourcing

4.2.2 Problem Formulation

Sub-game perfect equilibrium (SPE) outcomes are sought for the interaction between the seller and consumers. The backward induction method (to identify SPEs) ensures that consumer beliefs are consistent with the actual incentives for the seller. Further, this allows the seller to internalize the impact of strategic decisions made by its supplier and consumers. In the second period, the firm has an opportunity to revisit the pricing and architecture decisions - p_2 and A_2. The seller's optimization problem in the second period and its revenue under specialist-sourcing is presented in Equation 4.4. The seller sets its first period price p_1 and architecture A_1 to maximize the net present value of its revenue stream from the two periods (Equation 4.5). Here D_1, D_2 and D_u represent the number of consumers who buy the first version only, the second version only, and both versions, respectively. The formulations under other sourcing strategies are derived by making appropriate changes.

$$R_2^*\left(p_1, \theta, p_{s1}\right) = \begin{cases} \max_{p_2, A_2}\left(p_2\left(D_2 + D_u\right)\right) & \text{without upgrade pricing} \\ \max_{p_2, A_2}\left(p_2^n D_2 + p_2^u D_u\right) & \text{with upgrade pricing} \end{cases} \tag{4.4}$$

$$R_1^*\left(p_{s1}\right) = \max_{p_1, A_1}\left(p_1\left(D_1 + D_u\right) + \delta R_2^*\left(p_1, p_s\right)\right) \tag{4.5}$$

Sequential introductions may be introduced using the following two types of market segmentation[2]: (a) *Penetration pricing* or *Price Skimming*. In skimming, the first version is marketed exclusively to high-end consumers and the second version is sold to more low-end consumers. In penetration pricing, the first product is priced more aggressively to appeal to a wider consumer base than the second product is.

To derive the specific demands $D_i\left(p_1, p_2; \alpha, m, q_{tc}, q_s, p_{s1}, p_{s2}\right)$ for the two demand profiles, it is useful to define marginal consumers who are indifferent between any of consumption related actions The marginal consumer indifferent between actions a and b, v_{ab} is defined in Table 4.1.

[2]In general, it is also possible to obtain some other patterns that are known to be irrelevant in the equilibrium analysis (Ramachandran and Krishnan, 2007).

Actions	No purchase	Buy First version	Buy Second version
Version 1	$v_{01} = \frac{p_{S1}+p_1}{q_1}$	-	-
Version 2	$v_{02} = \frac{p_{s2}+p_2}{q_2}$	$v_{12} = \frac{\delta(p_2+p_{s2})-(p_1+p_{s1})}{\delta q_2 - q_1}$	-
Both	$v_{0u} = \frac{p_{s1}+p_1+\delta p_2}{q_1+\delta(q_2-q_1)}$	$v_{1u} = \frac{p_2}{q_2-q_1}$	$v_{2u} = \frac{p_{s1}+p_1-\delta p_{s2}}{(1-\delta)q_1}$

Table 4.1: Marginal Consumers for Different Prices and Product Qualities

Result 4.2.1 below shows the pricing conditions that are required for penetration and skimming segmentation strategies under various rates of innovation.

Result 4.2.1. Market Segmentation and Design Sourcing

Let $P_1 = \frac{q_1 p_2}{q_2-q_1} - \frac{p_1+p_{s1}-p_{s2}}{1-\delta}$ *and* $P_2 = \frac{p_2 q_1 - q_2(p_1+p_{s1}-p_{s2})}{q_2-q_1}$.

Consider first the case of specialist sourcing. Under Rapid Improvement ($\delta q_2 > q_1$)*, Penetration can be achieved if* $p_{s2} \leq P_1$ *and Skimming occurs if* $p_{s2} \geq P_2$.

Under Moderate Improvement ($\delta q_2 \leq q_1$)*, Penetration can be achieved if* $p_{s2} \leq P_2$ *and Skimming occurs if* $p_{s2} \geq P_1$.

The demands under Penetration and Skimming are given by

Penetration. $\mathcal{D}_0 = [0, v_{01})$; $\mathcal{D}_1 = [v_{01}, v_{1u})$; $\mathcal{D}_2 = \emptyset$; $\mathcal{D}_u = [v_{1u}, 1]$.

Skimming. $\mathcal{D}_0 = [0, v_{02})$; $\mathcal{D}_1 = \emptyset$; $\mathcal{D}_2 = [v_{02}, v_{u2})$; $\mathcal{D}_u = [v_{u2}, 1]$.

The corresponding conditions for open-sourcing are obtained by setting $p_{s1} = p_s$ and $p_{s2} = \theta p_s$.

Proof. All proofs, unless mentioned otherwise, are provided in the Appendix. □

4.2.3 Timing Inconsistency with Design Architecture and Pricing

Sequential innovations in the core technology allow the seller to revisit the pricing and architectural decisions that were made earlier. The seller is said to make *Architecturally Consistent* (AC) design decisions if the product's architecture does not change over time, i.e. product architecture A_1 ($A_t \in \{\mathrm{I},\ \mathrm{M}\}$) in the first period will not change as the core technology improves (i. e., $A_2 \doteq A_1$). To understand the importance of architectural consistency, consider a product that is integrated as the product improves, $A_1 = \mathrm{M}$ and $A_2 = \mathrm{I}$. Consumers who purchase the first version with the intention of upgrading their products will be unable to reuse their stable modules since the improved version is not amenable to modular upgrades. Consequently, changing the product's architecture negates the purpose of modular upgradability. While firms that serve industrial clients may have the ability to explicitly make such a design commitment, firms that operate in consumer markets must rely on signaling mechanisms to achieve the same end.

Consumers often buy early versions of modular upgradable products with the intention of replacing the improving module alone, which gives them a substantial implicit discount on the new product's price. However, it is not uncommon for firms to offer introductory discounts for newcomers to the market. Such practices allow firms to discriminate between repeat and new consumers in the second period. This lack of consistency in second-period pricing policies counteracts the benefit of purchasing early for the consumer. Therefore, the firm's commitment that preferential policies will not condition prices on a consumer's prior purchase decisions constitutes a certain kind of *Pricing Consistency* (PC), which is inevitable for modular sequential innovations. Often, PC is derived from the historical pricing policies followed by the seller or from market characteristics; for example, when isolating upgrading consumers is difficult. However, with the massive investments that have been made in customer tracking, the pressure might squarely be on the firm to convince consumers that consistent pricing can be expected in the second period.

Profit Maximization and Time Inconsistency

Modular upgradability under internal sourcing poses serious irresolvable time inconsistency issues. In the second period, the firm will set prices p_2 and p_{s2} such that new and repeat buyers can be perfectly distinguished. Strategic consumers foresee that the price they pay for the new product will thus depend on their prior decisions, early buyers do not expect to realize any savings due to modular upgradability. Therefore, the stable module pricing freedom (p_{s2}) under internal sourcing makes modular upgradability itself infeasible. Due to this reason, attention is restricted only to open- and specialist-sourcing as the firm's alternatives.

It is useful to consider, as the base case, an open-sourcing seller who can credibly announce that the second version will be similar in architecture to the first, and that in the second period preferential pricing will not be used to discriminate new and existing consumers. The optimal pricing decisions for such a seller are obtained by adding the constraints $A_2 \doteq A_1$ and $p_2^u = p_2^n = p_2$ to Problem 4.4 above. The optimal prices and revenues are presented in Appendix B.0.3. However, making such commitments to future product design and pricing policies is no easy task.

The seller who is unable to commit that architecture A_2 will be equivalent to A_1 might make inconsistent decisions for two reasons. Under open-sourcing, some of the surplus extracted from new consumers who purchase in the second period is channeled towards the stable module. By moving to an integrated architecture for the advanced version, the seller could extract more of the surplus from new consumers. Consumers are aware of this potential incentive for the seller to switch to an integrated architecture after improvements are realized in the core technology. Consequently, sellers without credibility cannot always pursue segmentation tactics that lead to the highest possible profits in a sub-game perfect equilibrium[3].

The second-period opportunism under open-sourcing is replaced with defensive pressures of appropriation under specialist-sourcing. When the advanced version is introduced, the stable module manufacturer sets a price p_{s2} that would maximize his share of the surplus extracted from consumers. The focal firm, in spite of its best intentions in the first period, would benefit by avoiding this pricing game for surplus appropriation in the second period. To eliminate the specialist's participation, the firm could make the new version of

[3]The case in which $A_1 \doteq$INT is discussed in § 4.3.3.

the improving module incompatible with the specialist's stable module. This action, which is tantamount to integrating the product, leads to design inconsistency and causes regret for consumers who intended to upgrade their products.

Now let us turn our attention to the impact of pricing consistency. First consider a firm that has invested heavily in acquiring customer data, as consumers increasingly buy products online. Suppose that in the second period, the seller sets the price of the improving module at p_2^n and p_2^u for new and repeat buyers respectively. Consumers could be justifiably fearful that their purchase decision might be used to condition the price of improved versions. Therefore, if the firm can offer special introductory prices to new consumers, first period consumers will definitely regret their purchase. When consumers can conceal their prior decisions however, such first-degree price discrimination is infeasible. While new consumers may not be able to imitate repeat buyers, repeat buyers may simply choose not to reveal their previous purchase history. This imposes the natural constraint that the second period prices for new customers must be greater than that for upgrading customers, $p_2^n \geq p_2^u$.

At the end of the first period, the market consists of some consumers who own the first version and the rest who don't. In many cases, the seller sets a low price for the first version to attract one-time buyers of the first version, thus hinting that the improved version as an exclusive high-end product subsequently. However, the seller may be able to drop the price p_2^n and attract new buyers for the improved product. When the seller low-balls p_2^n to a point where even first-period abstainers are enticed, consumers who did purchase early will regret their decision to commit to a relatively expensive first version. Anticipating the seller's incentive to drop its prices, consumers may not purchase the first version in spite of the low prices.

Due to these reasons, a seller who cannot adhere to consistent design and pricing policies will be unable to segment the market in a fashion that maximizes its profit. This is formally stated and discussed this in Proposition 4.2.2 below.

Proposition 4.2.2. a) Architectural Inconsistency

Modular upgradability does not result in a sub-game-perfect equilibrium solution, irrespective of whether the stable module is internally-sourced, open-sourced or specialist-sourced without additional pricing constraints. A modular upgradable architecture is not time-consistent under certain pricing regimes. Specifically, $A_2 \neq A_1$.

b) Pricing Inconsistency

Modular upgradable architecture is not guaranteed to lead to a profit-maximizing sub-game-perfect equilibrium solution without (additional constraints for) pricing consistency.

Interestingly, there are common threats among the specific reasons that lead to time-inconsistencies in product design and pricing policies for the various sourcing mechanisms. Under open-sourcing, the incentive to integrate the improved version arises from the fact that new buyers are indifferent to product design (and upgraders' regret is irrelevant). For example, suppose the qualities of the various modules are $q_{1c} = 4.8$, $q_{2c} = 12.8$, and $q_s = 2$. Let $m = 0.8$, $\alpha = 0.75$ and $\delta = 0.5$. Then, the overall qualities of the two modular versions are $q_1 = 4$ and $q_2 = 10$. When the open-sourced stable module costs $p_s = 1$ in the first period and falls to 0.5 later, the optimal prices are $p_1 = 0.875$ and $p_2 = 4.75$ (see analysis in Appendix B.0.3). At these prices, consumers in $v \in (.8125, 1]$ buy in the first period and those in $v \in (.525, .8125]$ wait for the second version. In the second period alone, however, by integrating the improved version the seller can force repeat consumers to abandon their older stable modules and pay a higher price to upgrade. This would increase its second period revenue to 2.493, which exceeds the revenue from the modular version by 10%.

In specialist-sourcing, the stable module manufacturer's opportunistic behavior in appropriating more of the surplus new buyers receive forces the focal firm to defensively integrate the improved product. Consider the second-period situation described above: $q_2 = 10$, $q_1 = 4$ and consumers in $v \in (.8125, 1]$ own the first version. Now, if the product remains modular, the equilibrium prices set by the firm and the supplier are $p_2 = 3.96$ and $p_{s2} = 2.08$ respectively. Whereas the firm's profit from this approach is 1.57, this can be improved by at least 37% if it eliminates the supplier by integrating the product. As a result, the strategic incentives of the supplier become a major contributor to architectural inconsistency when new buyers intend to participate in the second period market.

4.3. Segmentation and Sourcing Solutions

The analysis in § 4.2.3 shows that a seller might face challenges in selling modular upgradable products in a way that would maximize its profit. This gives rise to the following question: Can the seller ever offer modular upgradability to its consumers when the product is improving? This question is answered in two parts - In this section, a market segmentation and pricing approach is proposed, which can help sustain a modular upgradable product architecture in a sub-game-perfect equilibrium even without AC or PC. In § 4.4, I consider how these insights might be affected if the stable module is not open-sourced, but is offered by a specialist provider.

4.3.1 Guaranteeing Backward Compatibility

The key to achieving sub-game-perfect equilibrium under modular upgradability is guaranteeing that improved version will continue to be modular and backward compatible with the first version. In this section, I show that a seller without AC can signal its intent to adhere to modularity under penetration pricing. In particular, the seller should introduce the first version aggressively and implicitly commit to a backward compatible, modular upgradable architecture for the new version.

Proposition 4.3.1. Pricing Constraint for deriving Architectural Consistency

Sub-game-perfect equilibrium prices exist for a modular upgradable sequence of products even when the seller lacks the ability to commit to product architecture if $p_1 \leq \bar{p}_1$*, where*

$$\bar{p}_1 = \begin{cases} \frac{(1-\delta)q_1 - 2(1-\theta\delta)p_s}{2} & \text{if } \delta q_2 > q_1 \\ \frac{(q_2-q_1)q_1 - 2(q_2-\theta q_1)p_s}{2q_2} & \text{if } \delta q_2 \leq q_1 \end{cases} \quad (4.6)$$

Proof. The proof is provided for rapid sequential innovation ($\delta q_2 > q_1$). The proof for moderate sequential innovation is analogous.

Suppose the seller sets $p_1 \leq \bar{p}_1$. Looking forward, from the analysis in § B.0.3 that the seller's second period price p_2 is either $(q_2 - \theta p_s)/2$ (for Skimming) or $(q_2 - q_1)/2$ (for Penetration). For $p_1 \leq \bar{p}_1$, it can be shown that $P_2 - \theta p_s \geq (\delta q_2 (q_1 - 2\theta p_s) + \theta q_1 p_s)/2(q_2 - q_1) > 0$. Since $\theta p_s < P_2$, skimming is not an equilibrium if $p_1 \leq \bar{p}_1$. However, it can also be shown that $\theta p_s - P_1 \geq 0$. Therefore, the penetration pricing equilibrium is realized with second period price and revenue in Equation 4.7 below.

$$p_2^* = \frac{q_2 - q_1}{2};\ R_2^* = \frac{q_2 - q_1}{4} \quad (4.7)$$

Since this profit does not increase by integrating the product in the second period, keeping the architecture modular is an equilibrium solution. Therefore, the seller obtains pricing credibility by setting p_1 according to Equation 4.6. □

By limiting the price of the first improving module ($p_1 \leq \bar{p}_1$), the seller attracts a wide installed base in the first period. As the proof of Proposition 4.3.1 shows, such constrained pricing conveys to the consumers the seller's intent to pursue a penetration pricing scheme, where all second period buyers upgrade their older versions. Consumers are also aware the seller does not benefit by offering an integrated product to upgrading consumers alone. This gives the seller the derived ability to commit to modular upgradable architectures in the future.

The price $\bar{p}_1$ reflects the extent to which the focal firm should restrain itself to derive AC - a closer look at $\bar{p}_1$ provides some insights about the impact of various factors at work. As expected, the seller is able to set a higher price if the quality of the first improving module or the stable module improves. In addition, since the seller's focus here is to position the first version *relative* to the improved version, $\bar{p}_1$ is also non-decreasing in the quality of the improved module (q_{2c}). However, for higher values of discounting parameter δ, consumers are more willing to wait for the improved product - this makes achieving market penetration in the first period harder. As a result, $\bar{p}_1$ is non-increasing in δ. Finally, as expected $\bar{p}_1$ is decreasing in p_s, which is due to the fact that the stable module's price cuts into the consumer surplus the seller can receive. However, it is also interesting to note that $\bar{p}_1$ increases with θ. This is due to the fact that the seller finds it easier to penetrate the market in the first period if the price consumers pay for the stable module is expected to be high in the second period.

While Proposition 4.3.1 does not guarantee that the seller will modularize its product line, it gives us an important insight into how a modular upgradable family will be priced and positioned. From here on out, the discussion of modular upgradability will be restricted to the case in which the seller uses penetration pricing as described by Equation 4.6.

4.3.2 The Effect of Upgrade Pricing

From Proposition 4.2.2, there are instances in which an inability to commit to second period prices could affect the adoption of the early version. How can the seller derive pricing consistency to commit to a single price for the improved version? I show below that the seller may do so by constraining the first period price p_1 such that there will be no incentive to price discriminate in the second period.

Recall that the optimal second period price and profit for the seller when it does price discriminate in the second period are given by Equation 4.7. At this price of $p_2^* = (q_2 - q_1)/2$, note that previously inactive low-end consumers do not find the improved product attractive. The seller may find it attractive to target these low-end consumers in the second period by setting p_2^n at a sufficiently low level. However, as Proposition 4.3.2 shows, it is possible to eliminate this incentive in advance through penetration pricing.

Proposition 4.3.2. Upgrade Pricing Constraint for Pricing Consistency

Sub-game-perfect equilibrium combination of prices exist for a modular upgradable sequence of products even in the absence of pricing consistency if the seller *uses penetration pricing with a restricted first period price p_1^*, where*

$$p_1^* = \begin{cases} \min\left\{\frac{((1-\delta)q_1-2p_s(1-\theta\delta))}{2}, \frac{q_1\left(\sqrt{q_2(2q_2-q_1)}-q_2\right)-p_s(q_2-\theta q_1)}{q_2}\right\} & RSI \\ \min\left\{\frac{(q_2-q_1)(q_1-2p_s)-2(1-\theta)q_1p_s}{2\,q_2}, \frac{q_1\left(\sqrt{q_2(2q_2-q_1)}-q_2\right)-p_s(q_2-\theta q_1)}{q_2}\right\} & GSI \end{cases} \tag{4.8}$$

Proof. The proof is provided for rapid sequential innovation ($\delta q_2 > q_1$). The proof for moderate sequential innovation is analogous.

When $p_1 = p_1^*$ and $p_2 = (q_2 - \theta p_s)/2$, $\theta p_s < P_2$. Therefore, skimming is not achieved. When $p_1 = p_1^*$ and $p_2 = (q_2 - q_1)/2$, $\theta p_s \le P_1$. Therefore, penetration is achieved in the first period. Let $\hat{v}$ represent the lowest valuation customer who bought the first period product. Let the new optimal pricing strategy be $p_2^n = p_2^u$ $(= p_2)$ such that some consumers with $v < \hat{v}$ find the improved version attractive. The optimal second period price and profit are

$$p_2^*(\hat{v}) = \frac{(q_2 - q_1)((1+\hat{v})q_2 - \theta p_s)}{2(2q_2 - q_1)};\ R_2^*(\hat{v}) = \frac{(q_2 - q_1)((1+\hat{v})q_2 - \theta p_s)^2}{4q_2(2q_2 - q_1)} \tag{4.9}$$

When $p_1 = p_1^*$, $\hat{v} \le \frac{\sqrt{q_2(2q_2-q_1)}-(q_2-p_s)}{q_2}$. By setting the previously committed $p_{2c} = (q_2 - q_1)/2$, second period revenue $R_{2c}^* = (q_2 - q_1)/4$. When $p_1 \le \tilde{p}_1$, it can be shown that $R_2^*(\hat{v}) \le R_{2c}^*$. Therefore, the seller does not have an incentive to set p_2 different from $(q_2 - q_1)/2$. □

The intuition behind this result is as follows. If the first period price set by the seller for the improving module is sufficiently low, a wider segment of the market base is covered by the first version. This ensures that only consumers very close to the low end of the market are left out. In the second period, marketing the improved improving model to these consumers would entail price reduction for the lucrative segment also, thus placing a large negative externality on the pricing capabilities. As a result, such low-balling in the first period eliminates any interest the seller may have in seeking new consumers for the improved improving module.

4.3.3 Product Architecture and Market Segmentation

The results in § 4.3.1 and § 4.3.2 show that a seller without architectural or pricing consistency can achieve sub-game perfect price discrimination outcomes by positioning the early version as a mass-market product. Now, let us investigate if the seller would modularize the second version when it designs the first version as an integrated package. Does the seller face issues of architectural inconsistency in this case?

By modularizing the second version after using an integral architecture in the first period, the seller forces each second period buyer to spend θp_s of his or her reservation utility on the stable module. This is because the modular sequel is incompatible with an integrated predecessor. Further, the seller has already incurred the fixed cost of developing the capabilities for a functional stable module. Therefore, irrespective of whether penetration or skimming is used, modularization in the second period results in lower profits for the seller when $A_1=$ INT. Since shifting to a modular architecture in the second period is sub-optimal, selecting the integrated architecture in the first period creates AC to guarantee an integrated second version. This result, in combination with the results in § 4.3.1 and § 4.3.2 above, shows that the seller can generate an *inertial commitment to product architecture* through its own design and positioning choices in the first period.

Proposition 4.3.3. Architectural Consistency

The seller can guarantee that the architecture of the product will not vary as the core technology improves over time by using penetration pricing in the first period.

Proof. Suppose the seller develops both modules of the integrated first version in-house. From § B.0.2 above, it is evident that switching to a modular architecture in the second period would lower his revenue from the improved version. Suppose the first version is modular. From Proposition 4.3.1, a seller without AC has no incentive to switch to an integrated architecture for the second version under penetration pricing. Therefore, the seller can commit to invariant product architecture in the first period through penetration. □

Proposition 4.3.3 proves an interesting and strong connection between product design and marketing in the context of improving products. Although there may be several ways to design and market improving products, this result suggests that fundamental design attributes such as product architecture play a critical role in determining how the product should be marketed.

This proposition also establishes that selling the first version as a *basic* product and creating a wide installed base is necessary for rapidly improving technologies. It is interesting to note that this result is driven by a requirement to commit to product architecture rather than conventional reasons such as word-of-mouth effects or network externalities.

4.4. Strategic Interactions with Specialist Supplier

The analysis thus far is pertinent to markets where all the pricing power is concentrated in the hands of the manufacturer of the improving modules. This is applicable in situations where a generic stable module might have emerged, leading to its commoditization. However, in several industries, this power is shared between the producer of the improving modules as well the maker(s) of the stable modules. Such a distribution of pricing power can emerge when a dominant manufacturer can provide a stable module of relatively higher quality compared to his rivals, as in the case of examples such as noise-canceling headphones. Do the architectural and pricing consistency issues identified in § 4.2.3 continue to affect the IM even when the pricing power is shared? If so, are they exacerbated or weakened? In order to answer these questions, in this section, the interactions of the improving module manufacturer (IM) with the specialist stable module manufacturer (SM) are considered.

Let the quality of the specialist's stable module be ϕq_s, whereas the integrated stable module's quality is q_s. To focus on the case in which the IM will at least consider modularizing the product, the attention is restricted to the non-trivial case in which the specialist's quality exceeds the quality of an internally developed stable module, i.e. $\phi \geq 1$. To clarify that the overall qualities of integrated and modular products can be different, these are denoted by q_t^I and q_t^M respectively (in period t). Specifically, $q_t^I \doteq \alpha q_{tc} + (1-\alpha) q_s$ and $q_t^M \doteq \alpha q_{tc} + m (1-\alpha) \phi q_s$. The SM sets prices p_{s1} and p_{s2} for the stable module in the two periods; this forces the IM to take into account the SM's incentives in making its own pricing and development decisions. In order to continue the focus on product architecture itself, it is assumed that the marginal cost of producing the stable module is negligible.

The improving module manufacturer (IM), as seen in Proposition 4.3.1 above, might have an incentive to design the improved product in an integrated fashion in order to maximize its profit in the second period. Consequently, skimming the market is not feasible when the manufacturer cannot commit to product architecture. This result from the previous section also extends to the case in which the stable module is manufactured by a specialist. As a result, the IM uses the market penetration strategy in introducing the first version. However, the IM's pricing decisions in the penetration strategy are affected the changing incentives of the SM.

Recall that, in the penetration pricing equilibrium, all second period consumers merely upgrade their products by purchasing the improved module. In order to attract some of the low-end consumers (who did not purchase in the first period) to buy the improved product, the SM is willing to drop his second period prices severely. However, if the manufacturer of the improving module allows the SM to lower p_{s2} to the point of attracting new customers, some consumers who purchased earlier will regret their decision to do so. Therefore, to ensure that a penetration pricing strategy is successful in spite of the SM's incentives to work against it, further restrictions must be placed on the price of the improving modules. These conditions are derived in Proposition 4.4.1 below.

Proposition 4.4.1. Pricing Constraint to Manage Specialist Stable Module Provider

The emergence of a specialist provider of the stable module restricts the price of the first version of the improving module as $p_1 \leq \hat{p}_1$

The upper bound $\hat{p}_1$ *is given by*

$$\hat{p}_1 = \frac{\left(q_2^M - q_1^M\right) q_1^M - 2p_s q_2^M}{2q_2^M} \tag{4.10}$$

where p_s *is the price of the stable module in the first period.*

Further, in any penetration pricing equilibrium, $p_{s2} = 0$*.*

This implicit price limit $\hat{p}_1$ decreases with the price of the stable module p_s. In essence, the IM's task here is to ensure that the market is sufficiently penetrated when the first product is launched so that consumers at the low-end will not participate in the second period even if the SM offers deep reductions in the stable module's price. Since attracting these consumers is easier when the product is better, the bound increases with the quality of the first version, q_1^M. These results show that improving module manufacturer who is hindered by two constraints - architectural inconsistency and dependence on a SM - must introduce the products through penetration pricing, and further restrict the price of the improving module in order to manage the temptations of the SM.

This constraint does not affect the pricing decision of the IM under all circumstances. In particular, when the product is improving rapidly, the optimal prices under penetration pricing are unaffected by the presence of the SM. However, when the product's improvement is slower, the necessity to control the SM imposes an additional pricing constraint on the IM. In Proposition 4.4.2 below, the impact of this constraint on the optimal price of the first version when the stable module is manufactured by an SM is discussed.

Proposition 4.4.2. Pricing Rapidly Improving Modules in the presence of a Specialist Stable Module Provider

For an improving module manufacturer, under rapid sequential innovation, the pricing constraint for architecture consistency dominates the pricing constraint required to manage the specialist manufacturer in the second period.

In other words, under RSI, interactions with the stable module provider do not constrain the improving module manufacturer in pricing the improving module in making architecturally consistent decisions.

$$\hat{p}_1 > \bar{p}_1|_{\theta=0} \quad if \quad \delta q_2^M > q_1^M \tag{4.11}$$

It is quite interesting to note that rapid sequential innovation - in spite of the potential regret it creates for consumers - acts as a protective shield for the IM in its interactions with the SM. The IM's strategy to commit to modular upgradability and to control the SM are the same, i.e. appealing to a wide set of early consumers through penetration pricing of the first version. When the product is improving rapidly, the IM ensures that p_1 is lower than $\bar{p}_1$ in order to commit to modular product architecture (Proposition 4.3.1). Encouraging consumers to consider the first version when the product improves rapidly itself is harder to accomplish. Therefore, the bound $\bar{p}_1$ places such a stringent restriction on p_1 that the SM's strategic incentives to lower p_s have no effect on the IM's decision.

4.4.1 Pricing the Stable Module with a Strategic Supplier

If the IM designs the product as an integrated product, the profit it obtains could be lower than that obtained with a modular design, but the IM gets to keep all the profit itself. If the product is modular, the SM obtains a share of the additional profit by selling the stable module. To derive the price of the stable module which both the IM and the SM agree as a fair price, Nash Bargaining solutions are found for the interaction between the two (Fudenberg and Tirole, 1991). It is worth noting in deriving this price that the improving module prices p_1 and p_2 clearly depend on the prices of the stable module p_{s1} and p_{s2}. Further, the IM's choice for product architecture will itself depend on these prices.

Since many bilateral decisions of this kind are made after extensive deliberations, I focus on the bargaining prices for the stable module as a function of core component qualities q_{tc}, the internal stable module quality q_s and the SM's quality ϕq_s. Alternatively, the SM can be a price-setter, in which case the

SM would raise p_s to a level that makes the firm indifferent between modular and integrated architectures.

Proposition 4.4.3. Equilibrium Stable Module Price and Profits
Let q_t^M and q_t^I represent the qualities of the modular product with specialized stable module and the integrated product that can be offered, respectively, in period t.
The equilibrium price of the stable module agreed upon by the IM and SM in the first period is given as follows:

$$p_s^* = \begin{cases} \frac{q_s(1-\alpha)(m\phi-1)(1-\delta)}{4} & \textit{under Rapid Improvement} \\ \frac{q_s(1-\alpha)(m\phi-1)A(B+C)}{4D} & \textit{under Moderate Improvement} \end{cases} \tag{4.12}$$

where $A = \alpha^2 \left(q_{2c} - q_{1c}\right)^2$, $B = \alpha q_{2c} \left(2q_{1c} + q_{2c}\right) + \left(1-\alpha\right) q_s \left(q_{1c} + 2q_{2c}\right)$, $C = m\phi q_s \left(\alpha \left(q_{1c} + 2q_{2c}\right) + \left(1-\alpha\right) q_s\right)$ *and*
$D = (\alpha q_{2c} + \left(1-\alpha\right) q_s)^2 (\alpha \left(q_{1c} + q_{2c}\right) + 2\left(1-\alpha\right) m\phi q_s)(\alpha q_{2c} + \left(1-\alpha\right) m\phi q_s)$.
In equilibrium, the additional profit obtained by modularization obtained by the IM, $\Delta\Pi_I$, is given by

$$\Delta\Pi_I = q_s \left(1-\alpha\right) \left(m\phi - 1\right) \left(1-\delta^2\right)/8 \tag{4.13}$$

when $\delta q_2^M > q_1^M$ and $\delta q_2^I > q_1^I$.
Further, if the SM is a price-setter, the stable module price in the first period is given by $2p_s^*$.

The price of the stable module depends on the stable module's contribution to the overall performance of the product. When the module qualities are such that the product improves rapidly over time, it is easy to observe from Equation 4.12 that p_s^* increases both with the quality of the generic stable q_s as well as the stable manufacturer's ability ϕ. Even when the product is not evolving rapidly, numerical results show that the stable module prices are higher when the product's overall quality is derived to a larger extent from the stable (larger q_s or ϕ). When the product is evolving rapidly, the IM's additional profit from modularity ($\Delta\Pi_I$) is also increasing with q_s, ϕ and m because of the increased attractiveness of seeking a specialized stable. Interestingly, the additional profit due to modularity is also higher when the value of δ is lower. To understand this, note that when δ is lower, the IM places a greater emphasis on obtaining revenue earlier. Modular upgradability, combined with penetration pricing, encourages more consumers to commit upfront, and allows the IM to charge higher prices for the improving module. The consequent increase in first period revenue makes modular upgradability even more attractive when δ is lower.

Further, it is clear that $\Delta\Pi_I$ is positive only if the performance improvements attained by inviting the SM to produce the stable module exceeds the cost of ceding a portion of the profits to the SM as well as the quality lost due to modularity. Based on this observation, a necessary condition for modularization to be attractive can be established (Corollary 4.4.4). Recall that the quality of the modular product is affected by the product's inherent modularity m. Therefore, if the specialist is unable to offer a minimal improvement in the quality of the stable module that overcomes the quality loss, modularization is fruitless.

Corollary 4.4.4. Necessary Condition for Modularization

Modularization of an improving product with a stable module manufactured by a specialist will lead to a sub-game perfect equilibrium only if the specialist's component quality is sufficiently superior to generic stable modules

$$\Delta\Pi_I > 0 \quad \textit{only if} \quad \phi > 1/m \tag{4.14}$$

The modular architecture is not attractive unless $\phi m q_s$ is at least as high as q_s. In other words, the IM is interested in interacting with the SM only if the quality premium offered by the SM's stable module overcomes the quality loss due to the intrinsic non-modularity of the product. It is worth noting, however, that this lower bound for ϕ $\left(\underline{\phi} = 1/m\right)$ might have to be modified under two circumstances: First, if development costs would be incurred when the IM internally develops the stable module, a manufacturer could consider a specialist even if $\phi < 1/m$. Second, a modular architecture can be profitable if an off-the-shelf stable module is available at a price lower than p_s^* even if $\phi < 1/m$.

4.5. Development Investment under Modular Innovation

From the analysis thus far, it is clear that in order to sell improving versions of a product, the earlier generation should be broadly marketed and improvements should target only high-end consumers. Under this restriction, what is the incentive for a manufacturer to invest in product improvements?

Further, dependence on a specialist supplier of the stable module places tighter constraints on module pricing and design architecture, which further restricts the profitability of innovation. How would a strategic supplier's participation in completing the product affect the improving module manufacturer's incentive to innovate?

To understand a firm's incentives to innovate and the extent of investment, consider a situation where the rate of improvement depends on the amount of development investment made by the improving module manufacturer. Specifically, the IM incurs a development cost of $C_D\left(q_{2c}-q_{1c}\right)^2$ to develop the improved version. Such quadratic cost functions are typical of the way development investments are modeled in the literature. Note that the overall rate of sequential innovation, q_2/q_1, depends on the development cost C_D, as well as sourcing strategy used for the stable module (open- or specialist-provided). Therefore, depending on the development cost C_D, the optimal q^*_{2c} could lead to either rapid ($\delta > q_1/q_2$) or moderate ($\delta \leq q_1/q_2$) rates of product improvement. Naturally, the optimal rate of innovation q^*_{2c}/q_{1c} also depends on the prices of the stable module: in open-sourcing, $p_{s1}=kq_s$ and $p_{s2}=\theta kq_s$ ($k>0$ and $0<\theta<1$); the prices of the stable module in specialist-sourcing is given by Equation 4.12 above.

When the effective contribution from the stable module ($\left(1-\alpha\right)q_s$) is low, the seller is able to achieve a high overall rate of performance improvement by advancing the improving module alone. In Proposition 4.5.1 below, a basic insight is derived regarding the rate of innovation (or q^*_{2c}) when the stable module is obtained from competitive or strategic supplier(s), and its relationship with the quality of the stable module: if the stable module's contribution to performance is low, the innovation investment is independent of the stable module's quality, and the investment is at a level conducive to achieving rapid improvements in the overall quality. Specifically, the investment made yields rapid improvement when the effective contribution from the improving module is substantially higher than the contribution from the stable module.

Proposition 4.5.1. Optimal Innovation Rate and q_s

For any development cost C_D*, there exists a* $\bar{q}_s(C_D)$ *such that for all* $q_s < \bar{q}_s$

a) The optimal second period quality q_{2c}^* *is independent of* q_s

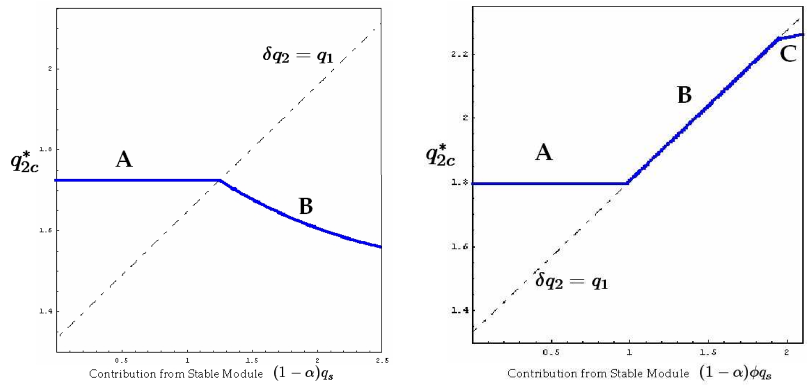
b) The modular product improves rapidly $\left(\delta q_2^M > q_1^M\right)$*.*

When the development cost C_D is low, the above condition on $q_s$is more easily met ($\bar{q}_s$ is larger), and the IM's investment in the improving module results in rapid sequential improvement in q_{tc}. In addition, under specialist-sourcing, we know from the previous section that when the innovation is rapid, the IM's pricing is unrestricted by the SM's presence. Consequently, rapid sequential innovation gives the IM decision-making independence from the strategic supplier of stable module. This is in addition to the fact that rapid innovation insulates the IM from the kind of pricing constraints that it must otherwise undertake in order to control the SM's behavior in the second period (Proposition 4.4.2). However, if the development cost C_D is higher, the IM will have to take into account ϕq_s, and the investment might lead only to a moderate improvement in the product and the q_{2c} itself depends on the stable module's contribution.

Investment with Strategic Supplier

To further understand how the rate of innovation depends on q_s, consider the numerical example in Figure 4.3. The dependence of the investment (or q_{2c}^*) on the stable module's contribution $(1-\alpha)\,q_s$ is remarkably different between open- and specialist-sourcing situations (Figures 4.3.a and 4.3.b respectively). For small values of q_s, even moderate investments may lead to rapid overall rates of improvement ($\delta q_2^M > q_1^M$ in region A of both figures). However, while the investment made by the IM is non-increasing with q_s under open-sourcing, it is monotonically non-increasing under specialist-sourcing. Let us examine the fundamental difference between the two external sourcing strategies that drives such diametrically opposite investment strategies for the IM. First, recall the modeling assumption that the quality of the two modules are substitutable in terms of their contribution to product quality (Equation 4.1). As a result, under open-sourcing (Fig 4.3.a), the improving module manufacturer is able to throttle the investment made in development as the contribution from the stable module becomes stronger. As q_s continues to increase, in region B, q_s becomes an important contributor to the product. The IM takes advantage of this contribution by reducing the investment it must make in order to make the products attractive to consumers.

However, there appears to be additional subtleties in explaining the



a. Open Sourcing **b.** Specialist Sourcing

Figure 4.3: Optimal Rate of Innovation

IM's incentives under specialist-sourcing (Fig 4.3.b). The fraction of total profits obtained by the each firm in the bargaining process is in proportion to the fraction of overall product quality that is directly derived from the firm's module. Therefore, as the quality of the stable module increases, strategic considerations lead the IM to expend more in improving q_{2c}, not less. This is in sharp contrast to the open-sourcing setting. As a result, as q_s continues to increase, at about $q_s = 1/(1-\alpha)$, the product's overall rate of improvement is only barely rapid $\left(\delta q_2^M = q_1^M\right)$. In region B, the IM elevates q^*_{2c} just enough to keep the product improving at a rate at which its pricing decisions are not constrained by the SM's incentives. Finally, as q_s becomes the dominant contributor to the product (region C), it becomes prohibitively expensive for the IM to maintain this torrid pace of innovation in the improving module. Yet, the IM continues to invest more in the improving module if q_s is larger.

The analysis in this section has helped identify some important differences in strategic considerations for a sequential innovator among various modes of externally sourcing non-improving components of an improving product. While it may be possible to leverage the advanced capabilities of the SM in designing the stable module, the IM also exposes consumers to opportunistic pricing by the SM. Further, the SM also demands a portion of the additional profit that is in proportion to the SM's contribution to the overall product. An important implication of this analysis is that specialist-sourcing may lead to rapid sequential innovation while open-sourcing of stable modules will result in a moderate pace of innovation under similar circumstances.

4.6. Discussion and Implications

Managing sequential innovation is a challenging task for firms especially when faced with demanding consumers and suppliers. In addition to the constant training and mobilization of launch, sales, and service teams, firms must also manage the purchase timing decisions of consumers who might decide to wait for improved products to become available in later periods. Modular upgradable product designs have been adopted by several firms selling improving products to industrial consumers, as in the case of semiconductor equipment, rackable servers, modular storage, and other examples.

However, modular upgradable consumer products continue to be few and far between. A key barrier that has been formalized in this chapter is the timing inconsistency the seller faces with respect to the design architecture and product pricing. Consumers who foresee the possible integration of future products refuse to consider modular upgradability for an earlier version. The seller's incentive to integrate an improved version might be amplified by the presence of a supplier of non-improving components who can appropriate some of the innovative fruits of the seller's labors. A forward-looking consumer might also predict the strategic supplier's role in driving the seller towards product integration.

I go beyond a negative result (the lack of subgame perfect outcomes) and show that carefully coordinating pricing and design decisions can enable the seller to make a commitment to future product design. When the seller attempts to skim the market by targeting the high-end consumers with an early version, there is a huge incentive to offer only an integrated advanced version. However, when the first version penetrates the market by following the pricing guidelines presented for the first period offering, only higher-end consumers upgrade later, and commitment to design becomes possible. This establishes an interesting link between a seller's product commercialization approach and decisions made in the design stages, which is a novel phenomenon.

In markets where the stable module of the product might be supplied by a strategic supplier, the focal firm would benefit by attracting new buyers when the advanced version of the improving module is launched. To employ the market penetration strategy, sellers in such markets have to be even more aggressive in pricing introductory versions. In addition to the design issues, the sellers ability to condition future prices on purchase decisions made by consumers in earlier periods is not desirable in modular sequential innovation when customer segments do not change over time. It was also shown that an aggressive penetration strategy can derive pricing consistency without the need to offer upgrade discounts in later periods.

These results - design inconsistency and the pricing-design coordination that is required to overcome this - have important implications for sellers in several classes of technology based improving products. For niche markets where consumer composition is not varying over time, the results in this chapter outline the importance of penetrating such markets with modular upgradable early versions, particularly when significant improvements are expected. While there are several reasons to create a large consumer base such as word-of-mouth effects, accelerating the learning experience, economies of scale and strengthening barriers to entry, these results clearly indicate that without a significant installed base it becomes difficult for the seller to extract any surplus created by efficient, modular design. These results also speak to the appropriateness of modular designs in dynamic marketplaces where the composition of consumers is in constant flux: in these marketplaces, the incentive to sell optimized integrated units to new consumers might exceed the profitability of offering modular upgrades to early adopters. This makes modular upgradability of earlier versions unattractive. However, when markets eventually reach saturation and the technology continues to improve (as in the case of many consumer electronic products such as digital cameras and audio players), a firm might consider applying the modular upgradable approach with coordinated pricing for revenue growth and profitability.

The analysis of the seller's interactions with a specialist provider of the stable module led to an interesting insight regarding the fundamental nature of such relationships in environments of technological change. Although it is assumed that the stable and improving modules contribute in an interchangeable (or substitutable) fashion to product performance, it was found that the improving module manufacturer escalates the pace of innovation if the stable module's contribution is higher. This counter-intuitive result originates from the fact that the two parties are engaged in constant competition for the consumer surplus that is generated by the products. Consequently, rapid sequential innovation becomes necessary for the improving module manufacturer to ensure favorable bargaining terms with a strategic supplier of complementary subsystems.

The analysis also suggests a dual-pronged strategy for innovators in industries certain dominant suppliers provide stabler components to consumers. First, with respect to pricing the modules, the innovator should penetrate the market aggressively with the earlier version in order to minimize the supplier's role in the second period. Skimming the market will only allow the supplier to play an active role in later periods and compete for the additional surplus generated by the innovation. Second, in order to insulate its own operations from the supplier's influence, the innovator would benefit by investing heavily and improving the product rapidly.

This is one of the first efforts to formalize modular design architecture and pricing in the context of sequential innovation. The results and insights from this chapter suggest that operational benefits and cost savings should not be the sole driving factor in adopting a modular approach, and a tightly coordinated design and pricing approach is needed to pursue modular sequential innovation. A number of stylized assumptions can be addressed in future work. Development-intensive products for which variable costs are insignificant compared to fixed design costs were considered in this work. For the sake of analytical tractability, the analysis was restricted to a two-period setting and assumed that the first period product is irrelevant in the second period due to the improvements in technology. The solutions provided are based on externally sourcing stable modules *exclusively* - it would be interesting to investigate in future work if partners who launch sequentially improving modules also face similar issues. Future work should also consider strategic roles played by vertical partners in a supply chain in jointly developing and marketing components of a modular system. Experimental and empirical testing of the results from this analysis are fundamental to obtain a clearer understanding of the phenomena described and the solutions suggested.

Chapter 5

Channels for Sequential Innovation: The Role of "Infermediaries"

5.1. Introduction

In the previous chapters of this dissertation, I discussed the importance of integrating decisions regarding product design, pricing and sourcing to successfully manage certain unique issues that confront a sequentially innovating firm. One of the central assumptions in these chapters, as in much of the literature on new product development - and sequential innovation in particular - is that consumers are completely aware of a product's value and are able to make perfect judgments at the time of purchase. However, little to no attention has been paid to the problem faced by a firm whose innovation leads to entirely new kinds of products that consumers may be ambivalent about. Consumers are often unsure of their valuation for a product's performance capabilities until they actually purchase and use it. In this chapter, I investigate the impact this uncertainty about valuations has on a sequential innovator's product strategy, and how he could enlist the participation of value-chain partners in addressing this issue.

All firms - small and large, entrepreneurial and established - depend on informative advertising to communicate the merits of their new products, but some aspects of a new product might need to be experienced by the end-user before the salient ways in which it addresses a segment's needs are clarified. When new kinds of products are introduced, intermediaries could play a vital, yet under-researched, role in retailing not just the physical goods themselves, but also in disseminating valuable information regarding the strengths of these goods. Some intermediaries specialize in performing this task specifically. For example, QVC and Home Shopping Network, which are television channels dedicated to demonstrating and retailing products to viewers. Our interactions with a product manager at a major manufacturer of printers in southern California shows the effectiveness of these channels in elucidating the various capabilities of a particular product: "(Our consumers) absolutely love the product once they realize it is designed for them. If they do not understand this, our product is just another printer". This firm also uses internal resources to channel this combination of products and demonstrations to consumers at specific forums like trade-shows. This observation is also supported by usage data, which shows that consumers who purchase the product through this channel understand the various capabilities of the product at a much deeper level compared to users that buy through traditional outlets such as retail stores (electronic and physical).

Since such intermediaries allow consumers to draw clear *inferences* about product characteristics without actually purchasing the product, we refer to them as *Infermediaries*. When a product is distributed through conventional channels, consumers are forced to buy a product in order to discover their valuations. An infermediary, however, typically demonstrates how the product might be used by the consumer and allows the consumer to ascertain their valuations in advance. While a firm can continue to provide the product to consumers who are sure of their valuations, infermediary channels provide an additional avenue to create a product-information bundle for the segment of a market that is uncertain about its valuation. Yet, infermediaries are not as commonly employed in distributing new products as one would expect. This gives rise to the following questions, which I investigate in this chapter:

1. What are the options available for a firm in dealing with uncertain consumers *without* the aid of an infermediary?

2. What is the specific role of an infermediary, if one is used for new product distribution?

3. Are infermediaries valuable channel partners under all circumstances?

4. What firm, product and market characteristics are most favorable for employing infermediary distributors?

To answer these questions, I consider a monopolist sequential innovator facing an improving technology curve. The market is segmented along two dimensions: a consumer is identified by her true preference for product quality and also by whether or not she is certain of her preference. Note that this is an important departure from current research on sequential innovation. One of the critical decisions made by the manufacturer in this model is determining whether an infermediary channel should be used to distribute the product to these uncertain consumers, and if so, which version of the product to distribute through the infermediary.

Whereas the infermediary performs an important function in leading hidden high-value consumers to buying the products, this channel is bound to be less efficient because of the additional effort involved. Subtler still, the analysis shows that even revealing true valuations to consumers before they purchase a product could be counterproductive to the manufacturer's cause. Most importantly, the analysis gives rise to a first-order understanding of the exact role of an infermediary channel in distributing new and improving products: The infermediary not only aids consumers in discovering their valuations, but helps the innovator in targeting high-value consumers without worrying lowering prices excessively.

The rest of the chapter is organized as follows. Section 5.2 outlines the modeling assumptions regarding the distribution of consumers along the two dimensions of differentiation, the infermediary and direct channels, and the hierarchy of decisions made by the innovator[1]. The main results are presented in Section 5.3, where conditions for using the infermediary are identified. An extension with the impact of complementary services or products is discussed

[1]We use the words "innovator" and "manufacturer" interchangeably in this chapter. We also use "uncertain segment" or "unaware segment" to indicate consumers who are unsure of their valuations.

in Section 5.4, followed by concluding remarks in Section 5.5.

5.2. Modeling Elements

We are concerned with the problem faced by a manufacturer who has two opportunities to launch new products. The qualities of products launched by the manufacturer in the two periods are q and γq ($\gamma > 1$), where γ represents the absolute improvement in product quality over time. The duration between the launch of the two products is measured indirectly by the amount by which profits, costs and benefits from the second period are discounted in the early period. Let this discount parameter be δ ($0 < \delta < 1$). I focus on the product positioning, pricing and channel selection decisions faced by the manufacturer for given levels of q and γ.

The market that the product caters to is comprised of both high- and low-end customers. Low-end customers obtain a life time service value of vq from a product of quality q, while high-end consumers obtain βvq, where $\beta > 1$ represents the marginal premium quality-conscious consumers are willing to pay for performance. Our focus in this work on a new class of products that consumers might not have experienced before: freshly conceptualized electronic goods and software applications often fit this category, particularly when their performance is focused on niche applications. Consequently, not all consumers in the market are aware of their preference (or individual valuation) for the product. Only a fraction α of all consumers in the market are aware of their valuation for product quality. Without loss of generality, the size of the market will be normalized to 1. Among the remaining $(1-\alpha)$ consumers who are uncertain about their valuation, consumers have either high valuation with probability α_u or low valuation with probability $1-\alpha_u$. In order to simplify the presentation in this chapter, it is further assumed that all consumers who are certain about their valuation value the product highly[2].

Note that consumers in our model - while they may be inconclusive about their valuation for a product - are perfectly rational and foresightful in decision-making. I also assume that all consumers are aware of market composition parameters such as α and α_u. While this may seem far-fetched, it is not unrealistic to assume that consumers have access to a general demographic data that are strongly indicative of consumer segmentation[3] or that publicly available industry analyst reports are able to project market composition with reasonable accuracy. Also, almost all papers on market segmentation issues have assumed that consumers have a high level of understanding regarding the composition of the markets they are a part of. Furthermore, any consideration of information asymmetry between the manufacturer and consumers hampers our attempt to obtain some first-order insights about the role of infermediaries.

[2]This is consistent with the idea that these consumers are sure of their interest in this novel product concept. Further, considering the presence of low-end consumers who are certain of their preferences only obfuscates the discussion without adding much insight.

[3]This also seems to bear true in the case of our motivating example.

5.2.1 Consumer Valuation Inference

Experiential Inference. Upon purchasing a unit of the product, a consumer who is previously unsure of his valuation for its services will be able to infer the same by using it. This inference usually comes only from experiencing the product when the product is sold through conventional distribution channels of the manufacturer. If an uncertain consumer purchases the lower quality product in the first period, he can use the experiential inference to gauge his value of upgrading to the improved version when it is launched.

Infermediary. Often, the manufacturer has the option to sell some units of a product through channels that specialize in communicating the salient value of a product to consumers by demonstrating their use before the point of purchase. Intermediaries who specialize in this mode of advertising include Home Shopping Network, QVC and ShopNBC. The manufacturer might also be able to demonstrate the product and take orders at trade shows and in-store demonstrations (in venues such as Costco). I focus on one particular attribute of such sales channels, namely, their ability to allow would-be users of the product to infer their valuations without forcing them to purchase the product itself. Since this medium allows this non-experiential inference before purchasing the product, it will be referred to as the *Infermediary* channel.

Distributing through the infermediary channel may entail either additional effort to demonstrate the product (when the manufacturer owns it) or a retailing margin might be levied by the infermediary (if it is an independent entity). This additional cost of using the infermediary is modeled through a simple parameter m $(0 < m < 1)$, which represents the per unit margin incurred on products sold through the infermediary. Since our focus on the valuation-discovery aspect of the infermediary, issues such as contracting with and competing against the infermediary are set aside for future extensions. Therefore, production costs are normalized to 0 for both product versions.

The manufacturer's decisions are dictated by the rate of product improvement and the ratio of valuations between the different segments, rather than the absolute levels of product qualities and valuations. Therefore, without loss of generality, parameters v and q are normalized and set to 1 in the rest of the chapter.

5.2.2 Channel Selection, Pricing and Consumption Decisions

Let us consider the decisions made by the manufacturer when the basic product has been designed and ready for production. In parallel, the manufacturer is designing the advanced product that will be launched in the second period. As mentioned before, the duration between these periods may be determined by any number of exogenous and endogenous factors such as: the development of the underlying technology, industry upgrade cycles, limited launch opportunities, etc. This duration - and consequently, the discounting over this duration δ - is predetermined.

The first decision for the manufacturer is deciding whether or not the infermediary should be utilized as a vehicle for educating consumers of their own valuation for product quality. If the intermediary will indeed be used, the manufacturer also needs to decide which of the products will be sold through this channel. While the infermediary allows customers to discover their valuations without forcing consumers to purchase a unit, there are two drawbacks in this approach: first, and obviously, distributing the product-information combination is more expensive (as reflected by parameter m); secondly, discovery before purchasing might alienate low-end consumers who might have bought the product otherwise. As the discussion below shows in detail, the decision to employ an infermediary depends on a number of technological and market variables.

The sequence of decisions made by the manufacturer and consumers are represented in Figure 5.1. First consider the case in which the manufacturer decides against using the infermediary. In the first period, he might sell the lower quality basic product exclusively to high-end consumers or to all consumers. If the product is sold exclusively, consumers who were previously uncertain about their valuations continue to be so when the manufacturer is ready to launch the improved product in the second period. On the other hand, if all consumers purchase, the market in the second period is divided into high- and low-end consumers who are both aware of their preferences. Note that the earlier division in the market was between consumers who knew their preferences and those who did not. In the second period, the manufacturer again decides whether or not the improved product should be priced to attract only high-end upgraders (if valuations were revealed) and if it should priced to appeal only to valuation-conscious consumers (if valuations were not revealed in the first period).

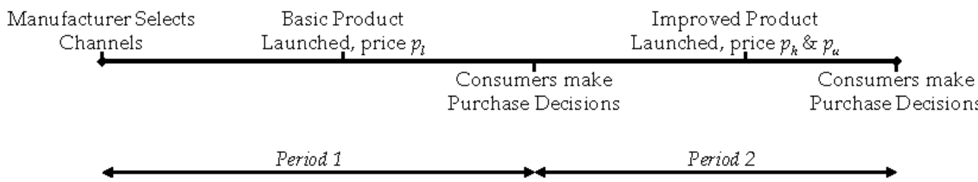


Figure 5.1: Decision Timeline

Suppose the manufacturer had chosen to engage the infermediary channel for distribution. The manufacturer and infermediary agree on the pricing and segmentation strategy they would pursue. In our model, the manufacturer easily controls the infermediary's behavior (if it is an external firm) - both directly, because he is the leader in their interactions, and also implicitly by controlling the supply of produced goods. If the basic version is sold through the infermediary, consumers immediately become aware of their valuations for the products. At this point, all valuations are revealed and the problem becomes one of managing revenues from the different segments of the market (á la (Ramachandran and Krishnan, 2007; Moorthy and Png, 1992)).

The prices of the basic and improved products are denoted by p_l and p_h respectively. In the particular case in which only high-end consumers purchased the basic product in the first period, it is assumed that the manufacturer will be able to offer a product upgrade at a special price p_u. It is clear in our model that the manufacturer would always prefer to sell products at the same retail price in both the infermediary and direct channels. Price differences between different channels (such as traditional and electronic) have been observed to be insignificant in a variety of product categories (Cattani et al., 2006; Young, 2001). Therefore, the prices at which products are offered in the two channels are the same at any point of time.

Each consumer has an opportunity to buy either one or both of the products. As rational agents, consumers are able to predict the price(s) at which the advanced product will be launched. Consumers self-select which product(s) they want to buy, and try to maximize their discounted net (expected) utility in the process. Naturally, all consumers with similar information (regarding their valuations) and common purchase history make identical purchase decisions.

5.3. Prices and Segmentation with Uncertain Consumers

5.3.1 Consumer Choices and Utilities

It is useful to first understand how consumers make purchase decisions before delving into the merits of using an infermediary. Figure 5.2 below shows the possible decisions an uncertain consumer can make in the two periods when the manufacturer does not employ an infermediary, and the (expected) net utility from each of those options[4]. If a consumer abstains from buying in the basic product, he also misses an opportunity to discover his preference for quality. Once a first period consumer discovers his valuation, he makes the

[4]Note that from an informed consumer's point of view, there is no uncertainty about the net value of different alternatives. Therefore, her decision tree is obtained merely by substituting $\beta_u = \beta$ or $\alpha_u = 1$ in the decision tree above.

decision that maximizes his utility from the second period.

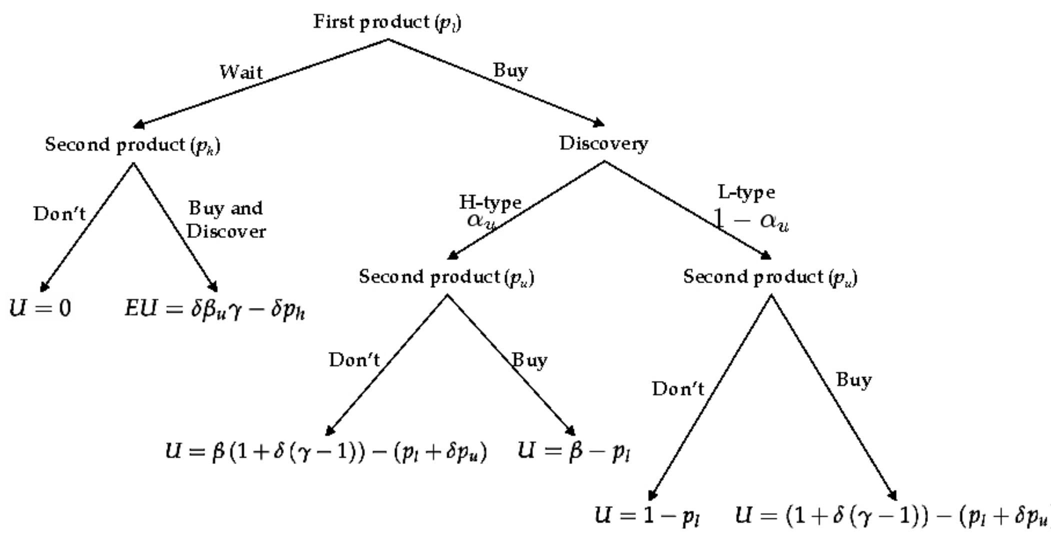


Figure 5.2: Decision Tree for Uncertain Consumer

The expected lifetime value of a product of quality q for an uninformed consumer is $\beta_u q$, where β_u represents a notional *expected marginal valuation* for such products. It may be formally defined as in Equation 5.1.

$$\beta_u \doteq \alpha_u \beta + (1-\alpha_u) \tag{5.1}$$

If valuations are discovered in the first period itself, there are no uncertain consumers when the improved product is launched, and consumers are willing to pay up to $(\gamma-1)$ or $\beta(\gamma-1)$ depending on their type. It is important to note that, unlike models in which consumers are perfectly aware of their preferences, even perfectly rational consumers might come to regret their purchase decisions in our model's equilibrium. For instance, an uninformed low-end consumer might purchase the basic product because his expected net utility of doing so justifies the action at price p_l; but realizing her true valuation for the product subsequently would lead to regret.

5.3.2 Pricing without Infermediaries

First, consider the case in which the manufacturer exclusively uses his traditional distribution channel. The firm's options in selling the product are as follows: In the first period, the firm may allow the consumers to infer their preference by lowering the price of the basic product. When the advanced product is launched, this would allow the firm to target only the high-value consumers without having to reduce the product's price. The firm may also choose to not reveal the valuations when the basic product is launched by catering exclusively to consumers who are sure that their valuation is high. Depending on the type of customers that participate in each period, there are four options for market segmentation: (i) All consumers buy both products (AA)[5], (ii) All consumers buy the basic product, but only high-end consumers upgrade (AH), (iii) Only high-end consumers buy in the first period with everyone buying the improved product (HA), and (iv) Uncertain consumers do not purchase either version (HH).

The manufacturer sets prices such that the participation constraints of consumers in the targeted segments are met in each period. Further, the

[5]The notation x_1x_2 with $x_t \in \{A, H\}$ denotes whether all consumers (A) or only high-end consumers (H) purchase in period t.

participation constraint for the purchase (and upgrade) paths of each segment should also be satisfied. Result 5.3.1 below gives the optimal prices for the manufacturer in each of these approaches. The net profits in each case are derived as

$$\pi_{xy} \;=\; n_l p_l + \delta\left(n_h p_h + n_u p_u\right) \tag{5.2}$$

where $x, y \in \{A, H\}$ and n_l, n_h and n_u represent the number of consumers who buy in the first period, number that buys in the second period only, and number of consumers who buy both versions. For instance, in the AH case, $n_l = 1$ and $n_h = \alpha + (1-\alpha)\,\alpha_u$.

Result 5.3.1. Pricing Improving Products without an Infermediary
The optimal prices for the manufacturer who does not employ an infermediary are as follows:
AA. $p_l = \beta_u\left(1 + \gamma\left(1-\delta\right)\right) - \delta\left(\gamma - 1\right)$; $p_h = \gamma - 1$.
AH. $p_l = \beta_u$; $p_h = \beta\left(\gamma - 1\right)$.
HA. *If special upgrade prices are offered* $p_l = \beta - \delta\gamma\left(\beta - \beta_u\right)$; $p_h = \beta_u\gamma$; $p_u = \beta\left(\gamma - 1\right)$. *If upgrade prices are not offered* $p_l = \left(1-\delta\right)\beta$ *and* $p_h = \beta_u\gamma$.
HH. $p_l = \left(1-\delta\right)\beta$; $p_h = \beta\left(\gamma - 1\right)$.

The HH approach, where only high-end consumers who are aware of their valuations purchase products, does not involve any price discrimination is straightforward to understand. In AA, all consumers buy both versions of the product, and represents a case where the manufacturer is able to take advantage of consumers' uncertainty about their preferences. In this case, the utility of purchasing both products for a low-end consumer is clearly exceeded by the total amount of money she parts with $(p_l + \delta p_h)$. Yet, as the improved product is priced at $p_h = \gamma - 1$, she finds it appealing to upgrade also. The manufacturer might discriminate between low-end and high-end consumers after revealing their valuations by lowering the price of the basic product. In AH, all second period consumers belong to the high-end type, but their number is greater than the original α that were aware of their high liking for the product. In this case, the manufacturer uses the basic product as a tool of valuation discovery and charges a premium price for the advanced version.

Discrimination need not be based on preferences alone, it may be also be based on consumers' knowledge about their preferences. This occurs in HA when the manufacturer uses special upgrade prices. Here, consumers in the second period continue to be unsure of their preferences, and pay the higher price p_h, compared to the lower upgrade price p_u paid by consumers who are sure of their valuation. In HA, the manufacturer decides whether or not to offer a special upgrade by comparing the profits. Naturally, for these upgrade prices to be viable, it is required that $\beta(\gamma - 1) < \beta_u \gamma$. Corollary 5.3.2 below summarizes the profits from each of these market segmentation approaches.

Corollary 5.3.2. Profits without an Infermediary

The profits for the manufacturer who does not em ply an infermediary in each of the market segmentation approaches are as follows:

AA. $\pi_{AA} = \beta_u (1 + \delta(\gamma - 1))$.

AH. $\pi_{AH} = \beta_u + (\alpha + \alpha_u (1 - \alpha)) \beta\delta(\gamma - 1)$.

HA. $\pi_{HA} = \alpha\beta\left(1-\delta\right) + \delta\beta_u\gamma$.

HH. $\pi_{HH} = \alpha\beta\left(1+\delta\left(\gamma-2\right)\right)$.

When the manufacturer reveals uncertain consumers' preferences only when the advanced version is launched (HA), he has the option of offering a special upgrade price, if indeed that is optimal. Yet, his profits from delayed discovery of identity is unaffected by the decision to offer an upgrade. To understand this, note that the revenue obtained from the uncertain group of consumers is independent of this decision. At the same time, depending on whether or not an upgrade will be offered for the improved product, the manufacturer adjusts p_l for the high-end consumers such that the overall revenue from this segment remains the same.

The segmentation approach that leads to the highest profits will be selected by the manufacturer. It is clear that this choice will depend on how fast the product improves, how the high- and low-end segments compare in terms of their marginal preference for quality, and the composition of different segments. Unlike other models that purely discuss the best ways to segment a given market over time, the manufacturer in our model also implicitly attributes a role for the basic product depending on which approach he pursues. More specifically, by choosing either AA or AH (as opposed to HA or HH), the manufacturer also uses the basic product as a tool of valuation discovery. This valuation discovery aids the manufacturer in distilling the market into segments of consumers who are completely aware of their preferences - particularly in AH, where early discovery of valuations aids in broadening the reach of the advanced product without forcing the manufacturer to lower its price. Proposition 5.3.3 below characterizes the conditions under which each of these approaches become optimal.

Proposition 5.3.3. Market Segmentation

There exist thresholds $\hat{\alpha}_u$, α_{u1}, α_{u2}, α_1, α_2, α_3, α_4 *and* α_5 *such that*

1. If $\gamma\delta > 1$ *and* $\alpha_u < \hat{\alpha}_u$*, then*

a. If $\alpha_u < \alpha_{u1}$*: AA is used for* $\alpha \in [0, \alpha_5)$*, HA is used for* $\alpha \in [\alpha_5, \alpha_3)$ *and HH is used for* $\alpha \in [\alpha_3, 1]$

b. If $\alpha_u > \alpha_{u1}$*: AA is used for* $\alpha \in [0, \alpha_5)$*, HA is used for* $\alpha \in [\alpha_5, 1]$*.*

2. If $\gamma\delta < 1$ *or* $\alpha_u > \hat{\alpha}_u$*, then*

a. If $\alpha_u < \alpha_{u2}$*: AA is used for* $\alpha \in [0, \alpha_1)$*, AH is used for* $\alpha \in [\alpha_1, \alpha_4)$ *and HH is used for* $\alpha \in [\alpha_4, 1]$

b. If $\alpha_u > \alpha_{u2}$*: AA is used for* $\alpha \in [0, \alpha_1)$*, AH is used for* $\alpha \in [\alpha_1, 1]$*.*

Proof. The proof and expressions for the thresholds are available in the Appendix. □

Proposition 5.3.3 gives several intuitions about how the rate of product development and distribution of consumer valuations influence how the manufacturer segments the market. Irrespective of the rate at which the product improves (γ or δ) and the proportion of high-end consumers in the unaware segment of the market (α_u), the manufacturer is overwhelmingly dependent on the high-end (or unaware) segment if α is closer to 1 (or 0). Therefore, he sells both products to all consumers if α is quite small, and sells both products exclusively to high-end consumers when α is high. Of course, if the unaware segment consists primarily of high-end consumers (high α_u: $\alpha_u > \alpha_{u1}$ or $\alpha_u > \alpha_{u2}$), the firm benefits by allowing them to purchase at least one of the versions.

The interpretation is more nuanced for intermediate values of α, that is when both the unaware segment and the high-end segment are significant pools of potential consumers. To understand this, consider the impact of revealing consumers' valuations through experiential discovery in the first period (AH) when the unaware segment is comprised mainly of low-end consumers ($\alpha_u < \hat{\alpha}_u$). Since low-end consumers are unwilling to pay a premium for product quality once their valuations have been revealed, the manufacturer would have access only to a small consumer pool when he launches the improved product. Consequently, when the performance improves rapidly ($\delta\gamma > 1$), the manufacturer would rather keep uncertain consumers in the dark in the first period, in order to maximize revenues through the advanced product. However, if high-end consumers constitute the majority of the unaware segment, allowing them to remain oblivious of their high valuations is counterproductive because the manufacturer will be forced to lower the price for the premium product in order to attract them, while also sacrificing the opportunity to sell the basic version to these high-value consumers. Therefore, when $\alpha_u > \hat{\alpha}_u$, price p_l is set low enough to encourage experiential discovery by all consumers.

While it is already clear that the rate of innovation (represented by γ or

δ) plays an important role in determining the manufacturer's strategy, a more refined picture emerges when one focuses on the thresholds in Proposition 5.3.3 above. The variation of these thresholds with respect to innovation variables γ and δ, and valuation difference between high- and low-end consumers β, is represented in Table 5.1 below. The threshold $\hat{\alpha}_u$ increases with both γ and δ - indicating that faster rate of innovation increasingly favors delayed revelation of valuations. This, of course, is in accordance with the logic described above. Secondly, when the innovation is slow (smaller γ or δ), the firm finds it difficult to depend exclusively on high-end consumers who are conscious of their valuations in both periods.

	$\hat{\alpha}_u$	α_{u1}	α_{u2}	α_1	α_3	α_4	α_5
γ	$\uparrow$	$\uparrow$	-	-	$\downarrow$	-	-
δ	$\uparrow$	-	$\downarrow$	-	-	-	-
β	-	$\uparrow$	$\uparrow$	$\downarrow$	$\downarrow$	$\downarrow$	$\downarrow$

Table 5.1: Sensitivity of Thresholds with respect to γ, δ and β
$\uparrow$ (and $\downarrow$) = non-decreasing (and non-increasing)

The fact that gradual innovation forces the manufacturer to appeal to the unaware segment is reflected in the fact that the thresholds α_{u1} increases with γ. If the duration between the advanced and basic product launches is short, however, the manufacturer does not lose significant first period revenues by encouraging experiential discovery, but benefits by increasing the pool of high-end upgraders for the improved version. Therefore, for higher values of δ (shorter inter-version times), the exclusive HH strategy is less likely to occur (α_{u2} is larger). However, the manufacturer would find it cumbersome to do so if the expected valuation of the unaware segment is significantly lower than that of high-end consumers. Because the manufacturer would be more inclined to ignore the unaware segment for larger values of α if β is higher, α_{u1} and α_{u2} increase with β. The thresholds α_1 through α_5 determine whether or not the uncertain segment is targeted with at least one of the products: the higher the α_i, the more likely that the uncertain segment will buy at least one product. Naturally, as β, the premium high-end consumers place on product quality, becomes larger, the uncertain segment becomes less relevant for the manufacturer. This is reflected in the negative correlations between these thresholds and β.

5.3.3 Using Infermediaries for Uncertain Consumers

The discussion thus far has centered on the comparison of options available to the manufacturer when the only way in which consumers gain an understanding of the products is by purchasing one. The presence of an infermediary channel creates additional options for the manufacturer by virtue of its ability to reveal valuations for consumers without forcing them to buy a product. At the same time this education would entail higher operating costs for the medium.

The manufacturer can either use the infermediary to distribute the basic version in the first period, the improved product in the second period, or both. Note that the infermediary will not be employed to distribute the improved product if uncertain consumers have already purchased the basic version and discovered their valuations. Also, the infermediary will not be employed to distribute the basic version in the first period unless the manufacturer intends to sell the product only to high-end consumers - both who were aware of their valuations (α), and those who were alerted by the infermediary ($(1-\alpha)\,\alpha_u$). In fact, there is a unique situation in which using the infermediary channel could be justifiable.

Proposition 5.3.4. Product Introduction with Infermediary

If the manufacturer uses an infermediary channel, the infermediary distributes only the first version.

Further, the infermediary sells the basic product only to high-end consumers.

The prices, depending on which consumers purchase the improved product, are given by

HA. *If special upgrade prices are offered* $p_l = \beta - \delta\gamma\,(\beta - 1)$; $p_h = \gamma$; $p_u = \beta\,(\gamma - 1)$. *If upgrade prices are not offered* $p_l = (1-\delta)\,\beta$ *and* $p_h = \gamma$.

HH. $p_l = (1-\delta)\,\beta$; $p_h = \beta\,(\gamma - 1)$.

Proof. The proof is in the Appendix. □

It is interesting that the infermediary is never used to distribute the second product. First consider the case in which the basic version was distributed through the infermediary and consumers are already aware of their valuations. Using the infermediary any longer would only result in reducing the manufacturer's unit margins without adding any value through the distribution of information. Now suppose that the infermediary was not used for the basic product, but is used only for the improved version. The manufacturer is making poor use of the infermediary because by deferring his role to the second period, the firm would miss the opportunity to obtain revenues from high-end consumers in the uncertain segment in the first period itself. The fact that the infermediary is never used to distribute the advanced product underscores the role of the basic version itself. The basic product, as a medium of demonstrating the valuation consumers have for this product category, acts as a vehicle of value communication instead of merely being another possible source of revenue for the firm.

With the specific part played by the infermediary in launching sequential innovations established by this result, it is now possible to identify conditions under which using this channel is indeed beneficial for the manufacturer. To keep the presentation simple, it is assumed in deriving Proposition 5.3.5 that the additional cost of using the infermediary m is not so high such that distribution through the infermediary is not viable for any value of α. The role of m itself can be understood by observing the thresholds below.

Proposition 5.3.5. Market Segmentation with Infermediary

There exist thresholds α_{u3}, and α_{i1}, α_{i2} and α_{i4} such that

1. If $\gamma\delta > 1$ and $\alpha_u < \hat{\alpha}_u$: AA without the infermediary is used for $\alpha \in [0, \alpha_{i1})$, HH with the infermediary is used for $\alpha \in [\alpha_{i1}, \alpha_{i4})$, and HH without the infermediary is used for $\alpha \in [\alpha_{i4}, 1]$.

2. If $\gamma\delta < 1$ or $\alpha_u > \hat{\alpha}_u$: AA without the infermediary is used for $\alpha \in [0, \alpha_1)$, AH without the infermediary is used for $\alpha \in [\alpha_1, \alpha_{i2})$, HH with the *infermediary is used for* $\alpha \in [\alpha_{i2}, \alpha_{i4})$*, and HH without the infermediary is used for* $\alpha \in [\alpha_{i4}, 1]$.

Further, if $\alpha_u > \alpha_{u3}$*,* $\alpha_{i4} > 1$ *and the infermediary is used all high values of* α.

Proof. The proof and expressions for the thresholds are available in the Appendix. □

Without the benefit of the above result, one might imagine that the role of the infermediary - as a channel for educating the uncertain consumer - would be more prominent when the number of consumers who are unsure about their valuations is quite high. However this intuition, as the above result shows, is not quite true. Proposition 5.3.5 shows that the infermediary's contribution is limited, and its use is counterproductive when the majority of consumers in the market are uninformed (low α).

Note that revelation of valuations is still an important priority for the manufacturer in the first period when α is low, but the infermediary is not the best vehicle to achieve it. However, as α, the proportion of informed consumers increases in the market, using the infermediary for revealing valuations in the first period becomes a more attractive option. If consumers who are uncertain about their preferences is quite small in number ($\alpha > \alpha_{i3}$) and if the uncertain segment comprises primarily of low-end consumers ($\alpha < \hat{\alpha}_u$), naturally, revealing valuations is not a priority for the firm.

An Illustration. To get a better understanding of why using the infermediary channel becomes more valuable for the manufacturer as the number of informed consumers increases, consider a simple situation where the manufacturer sells only one version of the product, i.e. the product does not sequentially improve over time. Let the value of using the product be equivalent to \$50 and \$150 for the low- and high-end type of consumers, respectively. First consider a market of 20 consumers with $\alpha = 0$ and $\alpha_u = .5$, i.e. all consumers are uninformed and there is an equal chance of a consumer's valuation being 50 or 100. The price at which the product can be sold without the infermediary, $p_{wo} = 100$, the expected value of the product, giving the manufacturer a profit of \$ 2,000. Once the infermediary is used, consumers realize their true valuations before purchasing the product. The manufacturer may either opt to sell the products to all consumers (at \$ 50 per unit) for a profit of \$ 1000, or sell only to high-end consumers (at \$ 150 per unit) for a profit of \$ 1500. Clearly, the manufacturer would avoid using the infermediary in this scenario, even before the inefficiencies of reduced margins are included.

Now consider the same market with the following difference: high-end consumers who are aware of their valuations constitute 50% of the market, i.e. $\alpha = .5$. Of the 20 consumers, 10 are aware of their higher willingness to pay for quality, and 5 of the remaining 10 who are unaware are high-end consumers also. If the infermediary is not used, the manufacturer may either price the product at \$ 150 per unit for the high-valuation consumers alone for a profit of \$ 1500, or set the price at \$ 100 per unit and garner a profit of \$

2000. However, introducing the product through the infermediary would allow him to do even better. Suppose the cost of distributing products through the infermediary is \$ 15 per unit (with $m = 0.1$). If the manufacturer uses the infermediary to sell 5 units to the previously uncertain high-end consumers at \$ 150 per unit (with a margin of \$ 135 per unit), and sells 10 units to the other high-end consumers at \$ 150 apiece, his total profits are \$ 2175, which substantially exceeds both options for selling the product without the infermediary.

In illustrating how the infermediary becomes an important value-chain partner when the informed section of the market is larger, it also crisply illuminates the exact manner in which the infermediary adds value to the manufacturer's operations. Specifically, the important role of the pre-purchase education provided by the infermediary is not to increase the revenue obtained from the uncertain segment itself; in fact, the infermediary's activity in this regard is counterproductive. The real benefit of using the infermediary is that informing low- and high-end consumers of the uncertain segment obviates the need for the manufacturer to sacrifice profits from informed high-end consumers. It is in this protective role that the infermediary becomes a useful agent when the size of the informed high-end market segment is sizable.

5.4. Extension: Complements and Services

As shown in prior chapters, consumers of improving durable products often need to purchase peripherals or complementary goods and services to successfully use the product they obtained. The necessity of these complements is true of a broad class of products - from automobiles to software to consumer electronics. In fact, in certain product categories, including the motivating photo-printer market, these complements are not only necessary for consumers, but an important driver of revenue for the manufacturer. In this section, I attempt to develop a rudimentary model of complements consumption, and obtain basic insights regarding the influence of complements in the channel selection decision.

5.4.1 Model

As before, the fundamental utilities derived from the basic and advanced products are v and γv for a consumer of type $v \in \{1, \beta\}$ - and these determine their reservation prices for a product or upgrade. In each period, consumers directly buy complements for the product they own from the manufacturer, even if they had obtained the product itself through the infermediary. The amount of complements necessary for a consumer to fully derive the benefits of the product depends both on the quality of the product and on the consumer's type[6].

I make certain assumptions about the profit accrued from complements based on the models and results of prior researchers who have confronted the issue of joint consumption of durable goods with complements (Bhaskaran and

[6]It is assumed that even a previously uncertain consumer recognizes his valuation immediately or shortly after purchasing her first unit.

Gilbert, 2005; Kühn and Padilla, 1996). First the quantity of complements consumed by a consumer in any duration of time - and therefore, the profits accrued - increases with both with product quality q and consumer valuation v. Second, there could be diminishing returns from increasing the amount of complements consumed when the product quality improves. The following model of margins from complements captures these facets in a succinct manner.

$$\begin{aligned} r^c(q,v) &= kqv \\ r^c(\gamma q,v) &= k\theta\gamma qv \end{aligned} \tag{5.3}$$

The revenue per period from complements, r^c, increases with qv. The parameter θ $(0<\theta<1)$, captures the diminishing marginal increase in complement consumption with product quality. While the model does not detail the entire gamut of pricing and consumption decisions by the manufacturer and consumers, it does serve as a simple, yet useful, framework for our analysis.

5.4.2 Analysis

Since pricing decisions for complements are not considered, the optimal prices for the products continue to be dictated by their qualities and market segments alone. Based on prices from Result 5.3.1 and Proposition 5.3.4, the profits from various market segmentation approaches with complements can be derived (similar to Corollary 5.3.2).

Result 5.4.1. Profits with Complements

Without Infermediary:

AA. $\pi_{AA}^{c} = \pi_{AA} + (1 + \delta\theta\gamma)\left(\alpha^{h}k\beta + \alpha^{l}k\right).$

AH. $\pi_{AH}^{c} = \pi_{AH} + \left(\alpha^{h}k\beta + \alpha^{l}k\right) + \delta k\left(\alpha^{h}\theta\gamma\beta + \alpha^{l}\right).$

HA. $\pi_{HA}^{c} = \pi_{HA} + k\alpha\beta + \delta k\theta\gamma\left(\alpha^{h}\beta + \alpha^{l}\right).$

HH. $\pi_{HH}^{c} = \pi_{HH} + \alpha k\beta\,(1 + \delta\theta\gamma).$

With Infermediary:

HAI. $\pi_{HAI}^{c} = \pi_{HAI} + k\alpha^{h}\beta + \delta k\theta\gamma\left(\alpha^{h}\beta + \alpha^{l}\right).$

HHI. $\pi_{HHI}^{c} = \pi_{HHI} + \alpha^{h}k\beta\,(1 + \delta\theta\gamma).$

where $\alpha^{h} = \alpha + (1 - \alpha)\,\alpha_{u}$ *and* $\alpha^{l} = 1 - \alpha^{h}$ *represent the overall proportion of high- and low-end consumers in the market.*

The manufacturer determines whether to use the infermediary, and which introduction approach to pursue, by comparing the profits above. It is possible to derive thresholds that determine the optimality of various policies and show that they are indeed structurally quite similar to those identified in Propositions 5.3.3 and 5.3.5. However, in order to obtain some preliminary insights on how the manufacturer's increased reliance on complements affects the role of the infermediary, I consider some numerical examples.

Recall from Proposition 5.3.5 earlier that the value of introducing the basic product through the infermediary increases when the proportion of high-end consumers who are aware of their valuation increases. This is confirmed by the example in Figure 5.3 below. The number of consumers who are unaware of their high valuations, however, has the opposite effect on the channel selection decision. If the uncertain segment is dominated by high-end consumers, their expected valuation for product quality is high (because β_u increases with α_u).

In this case, the manufacturer would be able to entice these consumers to purchase the basic version of the product without needing to reduce its price significantly. As a result, the infermediary's role in aiding valuation discovery is exceeded by the additional expenditure for the manufacturer. Therefore, for high values of α_u, the manufacturer prefers to sell the product through his direct channels.

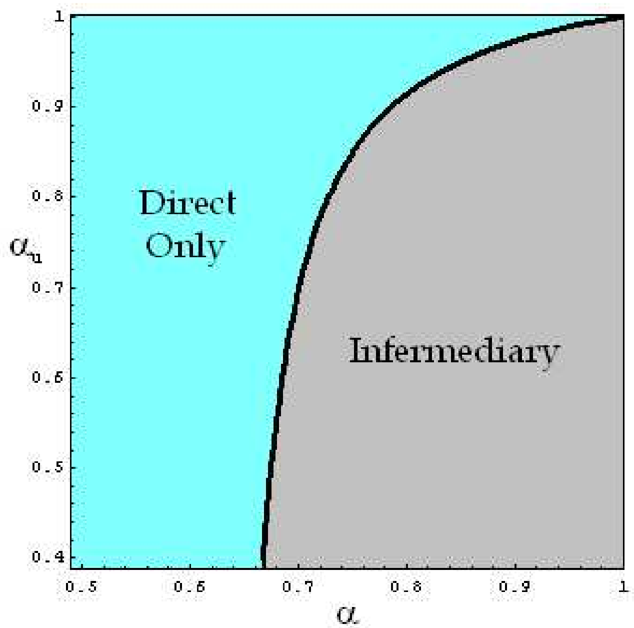


Figure 5.3: Channel Selection for different α and α_u

There is another important advantage of selling through the direct channel: although some consumers may find, after purchasing the product, that their valuations are too low to justify the price they have paid for it, they will still continue to use the product they purchase. This activity contributes to the complements-driven component of the manufacturer's revenue. This, however, would not occur if the infermediary distributes the product. These low-end consumers would use the demonstrative information provided by the infermediary to avoid buying the product, shutting off a line of revenue for the manufacturer. Consequently, as Figure 5.4 shows, an increase in reliance on complements for profits would result in limiting the role of the infermediary[7].

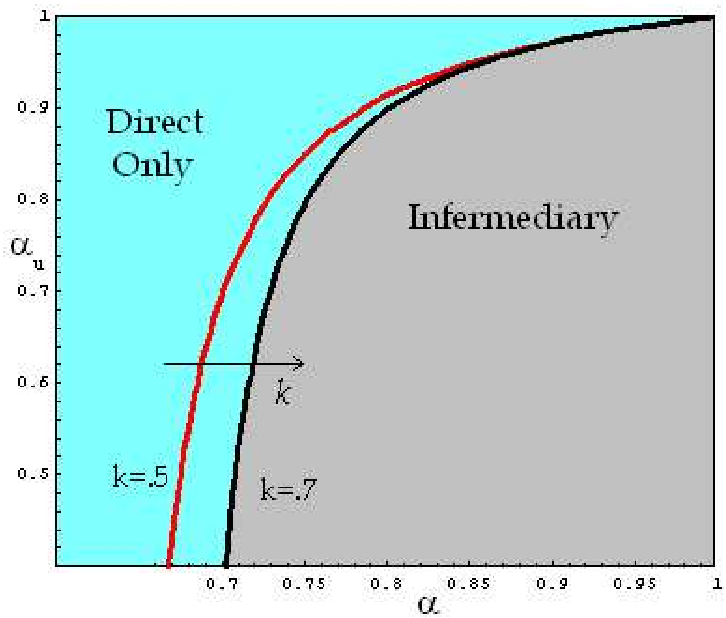


Figure 5.4: Channel Selection for different α and α_u with effect of k

Figure 5.5 shows this impact of complements more explicitly. As complements become more important to the manufacturer's profit (higher k), he

[7]This result may be tempered, or even reversed, in the context of several products. For example, if demonstrations by infermediaries also converts consumers into prolific users of the product, consumption of complements would be higher for consumers who buy through the infermediary. This facet of the problem deserves greater attention, which I intend to devote in the near future.

considers the infermediary only for substantially larger values of α. In other words, unless the market is saturated with a great number of high-end consumers, the infermediary's help in extracting product-related surplus from them is far outweighed by the alienation of low-end buyers of complements that the infermediary causes.

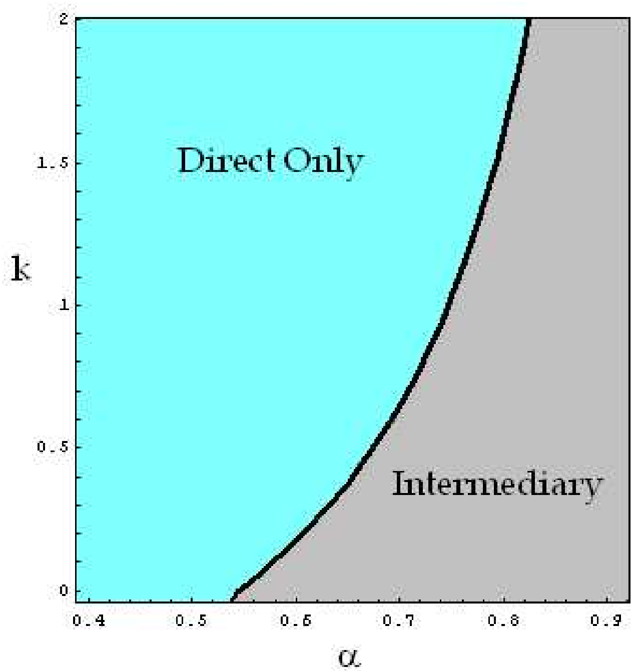


Figure 5.5: Channel Selection for different α and k

It is also interesting to see the interaction between the importance of complements and the constitution of the uncertain segment also. While it continues to be true that the infermediary channel is useful only when the product-revenues are much greater than the complements, the manufacturer prefers to use the infermediary even for large values of k if the uncertain segment consists of a larger number of low-end consumers. In effect, the decision to use this channel hinges on whether the manufacturer would find it attractive to exploit the uncertainty of consumers to generate complement sales or if isolating (and not catering to) low-end consumers improves the product prices for high-end consumers. When α_u is lower, appealing to the uncertain segment requires greater price drops; these are avoided by using the infermediary, even if that results in lower consumption of complements.

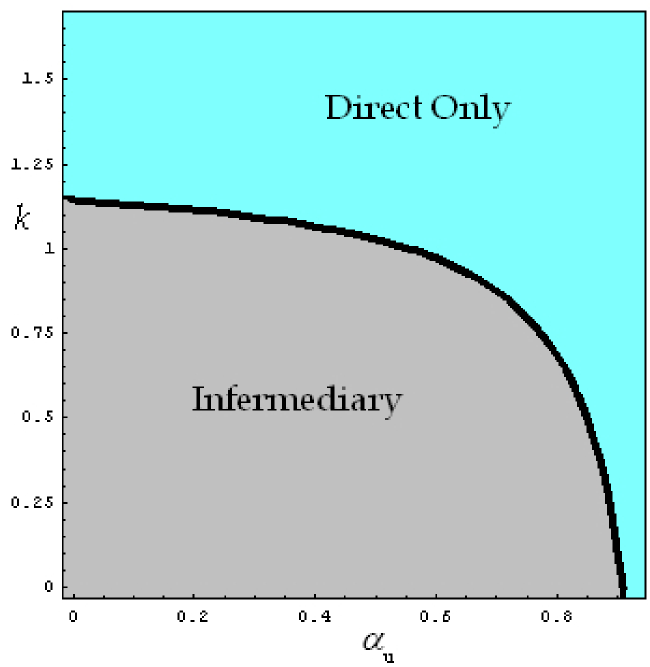


Figure 5.6: Channel Selection for different α_u and k

5.5. Conclusion

Often, when breakthrough innovations in technology lead to entirely new product categories, information regarding the functional attributes of these products are not widely available. As a result, consumers - including those whose concerns the product directly addresses - might remain unsure of their valuations for the product. Some information channels and modes of distribution specialize in educating consumers in a targeted fashion about the utility they would derive from these new products. Motivated by the experiences of a product manager trying to establish a new line of printing solutions, I have attempted to identify and derive some first-order insights regarding this specific role of distributors as *infermediaries* in this chapter. While this appears to be an attractive channel for distribution, one finds that they are used by only a few manufacturers for only a limited set of products.

The results in this chapter show that the infermediary is not always a useful ally in pursuing consumers who are uncertain about their valuations. In outlining situations under which the infermediary may or may not be desirable to have, this chapter also clarifies the underlying purpose served by such channels. By helping only high-value consumers identify themselves, the infermediary insulates the manufacturer from the cannibalizing influence of consumers who are less demanding of product performance. The demonstrative activities of the infermediary are unlike the demand-enhancing role of retailers (Lal, 1990; Xia and Gilbert, 2007). I also extend this insight to situations where the manufacturer also provides complementary services and products after consumers purchase the product.

Managers of new product categories in many sectors could benefit from this analysis. When a new product category emerges, infermediaries might seem to be efficient mediums to educate consumers who are uncertain of their values. But the analysis suggests that it can be counterproductive, particularly when the awareness about the product is quite low in the market. In these circumstances, which are more typical of entrepreneurial innovators whose products are publicized or used to a lesser extent, it is best for the manufacturer to use available pricing levers to popularize the product instead of using infermediary channels.

There are many ways to extend this research. First, the analysis could be advanced to understand the product design and pipeline management implications in the presence of infermediaries. The role of production and development costs have been ignored in order to focus on other aspects of the problem, but can be brought into the fold of a more evolved model. However, numerical examples and intuition suggest that the effect of production costs would be to favor the espousal of infermediaries as a serious value-chain partner. Finally, and perhaps most importantly, the role of infermediaries should be broadened - for example, there is evidence (both anecdotal and empirical) to suggest that the demonstrations conducted by infermediaries not only lead to a greater understanding of the product's capabilities, but also contribute to better use of the product by the average consumer.

Chapter 6

Concluding Remarks

Sequential innovation, while becoming increasingly important for sustainable profitability, also presents firms with a unique blend of challenges. In this dissertation, I identify and focus a trifecta of these issues and investigate how coordinating decisions design, sourcing and distribution decisions with downstream pricing decisions helps an innovator in managing these problems. To understand the specific challenges of sequential innovation, three longitudinal models of innovation, which capture facets of the business environment that are typically under-represented in the more popular cross-sectional analyses found in the literature. The results in these chapters show that in order to reap the rewards of sequential innovation, a firm must perceptively consider the following decisions much in advance of the arrival of the innovation itself: architectural elements of the product's design, managing developers and suppliers of critical components, and selecting effective channels for product distribution. Occurring at various conceptual stages of product development, each of these decisions play an important role in determining whether or not a firm is able to reward itself for constantly offering better products to its consumers. These results have important implications not only for established firms that are dominant in their areas, but also for entrepreneurial ventures that are trying to legitimize their product concepts.

In this first step at formalizing managerial issues in sequential innovation, I have focused on three important questions. Chapter 3 demonstrates that localizing performance improvements and developing the product to be upgradable in modules offers consumers the opportunity to buy into the technology instead of apprehensively rejecting it in the face of rapid obsolescence. As the list of firms that struggle to juggle improving products and balking consumers continues to grow, this research identifies a fundamental decision variable that could unlock the puzzle for many of these companies. In Chapter 4, I consider how the product design decision evolves over time when the firm is under constant scrutiny from consumers and pressure from suppliers. The inability of the firm to commit to a backward compatible, modular upgradable path of sequential innovation is framed as a time-inconsistency issue. This makes the case for an even tighter coordination between design and sourcing strategies on the one hand and pricing and segmentation strategies on the other. These results underscore the importance of a long-term perspective in viewing the evolution of the underlying technology in finding product designs and supply partners. Finally, in Chapter 5, I focus on revolutionary products that end-users might not have had the opportunity to sample earlier. Faced with consumers who are unsure of their own valuations for the product, an innovator might be able to use special channels of education to distribute the products. Analysis of the model shows that an innovator needs to be extremely careful in committing to these channels because of their potential to alienate some segments. Understanding the exact fashion in which a value-chain partner operates, and assimilating the precise implications of these operations for an innovator's own objectives, are shown to be central to this channel selection decision.

The analysis in this dissertation and the models used to derive them can be extended, varied and improved in a number of ways that would enhance our understanding of sequential innovation. One of the most important considerations that needs to be a part of any future discussion on the topic is Competition. The nature and impact of competitive forces - at the level of the innovator, sources of production or distribution - represent an enticing and valuable set of potential discoveries. Another challenging extension of these results could come from expanding the time horizon under consideration. Finally, this dissertation only broaches some broad aspects of the managerial issues faced by a sequential innovator. Delving deeper into operational issues such as capacity planning (under constant technological change) and supply chain contracts (for products and components under threat of technological obsolescence) represent a core of future extensions that would bring normative research insights closer to the realm of applicability.

Appendices

Appendix A

Design Architecture and Introduction Timing for Rapidly Improving Industrial Products

A.0.1 Proof of Property 3.3.1: Segmentation Patterns for RSI

SP-1. $p_s \leq P_1$

Under these conditions on prices, we know that $v_{01} \leq \min(v_{0u}, v_{02})$ $\Leftrightarrow$The lowest end marginal customer buys in the first period alone. And $v_{01} \leq v_{u1} \leq v_{12}$ $\Leftrightarrow$The next marginal customer buys in both periods. Also, from Lemma A, we know that v_{u1} is the final marginal customer. Therefore, customers in $v \in [0, v_{01})$ do not participate; $v \in [v_{01}, v_{u1})$ buy in the first period; $v \in (v_{1u}, 1]$ buy in the first period and upgrade when the improved product is available.

SP-2. $P_1 \leq p_s \leq P_2$ and $p_1 + (1-\delta)p_s \leq (1-\gamma\delta)f(q_1)$

In this pattern, $v_{01} \leq \min(v_{0u}, v_{02})$ $\Leftrightarrow$The lowest end marginal customer buys the first product only. $v_{01} \leq v_{12} \leq \min(v_{u2}, v_{u1})$ $\Leftrightarrow$The next marginal customer buys in the second period only. The final marginal customer is indifferent between buying in the second period and buying in both periods. Hence, $v \in [0, v_{01})$ do not buy; $v \in [v_{01}, v_{12})$ buy in the first period; $v \in [v_{12}, v_{u2})$ buy in the second period; $v \in [v_{u2}, 1]$ buy in the first period and upgrade.

SP-3. $\quad P_1 \leq p_s \leq P_1$ and $p_1 + (1-\delta)p_s \geq (1-\gamma\delta)f(q_1)$

In this SP, $v_{01} \leq \min(v_{0u}, v_{02}) \Leftrightarrow$the lowest end marginal customer buys in first period alone. $v_{01} \leq v_{12} \leq \min(v_{u2}, v_{u1}) \Leftrightarrow$the next marginal customer buys in the second period only. The customer with the lowest valuation for quality who is indifferent between buying in period 2 and buying in both periods is v_{u2}.

$p_1+(1-\delta)p_s \geq (1-\gamma\delta)f(q_1) \Leftrightarrow v_{u2} \geq 1$. There is no customer who finds buying in both periods optimal. This results in a consumption pattern in which $v \in [0, v_{01})$ do not buy; $v \in [v_{01}, v_{12})$ buy in the first period; $v \in [v_{12}, 1]$buy in the second period.

SP-4. $\quad p_s \geq P_2$

When second period prices are expected to be sufficiently low, $v_{02} \leq v_{0u}$ and $v_{02} \leq v_{01} \Leftrightarrow$ the lowest end marginal customer buys in the second period alone. Also, $v_{01} \leq v_{u1} \leq v_{12}\Leftrightarrow$The next marginal customer buys in both periods. From Lemmas A and B, we know that v_{u2} and v_{02} are the only marginal customers in this range of prices. Therefore, $v \in [0, v_{02})$, do not buy in either period; $v \in [v_{02}, v_{u2})$ buy in the second period; $v \in [v_{u2}, 1]$ buy in the first period and upgrade.

A.0.2 Proof of Proposition 3.3.3: Proprietary Modular Architecture

We present the proof for the Rapid Improvement case below. The proof for Gradual Improvement is similar and straightforward.

Pricing in SP 1. To ensure SPE outcomes, we will begin by solving the second period problem:

$$R_2^* = \max_{p_2} \{p_2 (1 - v_{1u})\}$$

Solving this, we obtain $p_2^* = \frac{f\left(\beta q_2^\alpha\right) - \gamma f(\beta q_1)}{2}$ and $R_2^* = \frac{f\left(\beta q_2^\alpha\right) - \gamma f(\beta q_1)}{4}$. We now turn our attention to the first period problem, while constraining the solution to satisfy the conditions for SP 1.

$$\begin{aligned} \Pi^* &= \max_{p_s, p_1} \{(p_s + p_1)(1 - v_{01}) + \delta R_2^*\} \\ & s.t. \quad p_s^* \leq P_1 \end{aligned}$$

The unconstrained solution for this problem satisfies $p_s^* + p_1^* = f(\beta q_1)/2$. As shown below, any solution of this type violates the constraint $p_s^* \leq P_1$.

$$p_s^* \leq P_1 \Leftrightarrow p_s^* \leq \frac{f(\beta q_1)(1 - \gamma\delta)}{2(1 - \delta)} - \frac{p_1^*}{1 - \delta} \Leftrightarrow \frac{\delta p_1^*}{1 - \delta} \leq -\frac{f(\beta q_1)\gamma}{2} < 0$$

The optimal constrained equilibrium prices and profit are

$$p_s^* = \tfrac{f(\beta q_1)}{2},\ p_1^* = 0,\ p_2^* = \tfrac{f\left(\beta q_2^\alpha\right) - \gamma f(\beta q_1)}{2}$$
$$\Pi^* = \tfrac{f(\beta q_1)}{4} + \delta \tfrac{f\left(\beta q_2^\alpha\right) - \gamma f(\beta q_1)}{4}$$

Pricing in SP 2. In the second period, the firm tries to sell to $v \in [v_{12}, 1]$. To ensure that it is able to sell to the available segment of the market while maximizing its revenue, the firm will solve the following problem.

$$\begin{aligned}&\max_{p_2}\left\{p_2\left(1-v_{12}\right)+p_s\left(1-v_{u2}\right)\right\}\\&\text{s.t.}\\&v_{12}f\left(\beta q_2^{\alpha}\right)\geq p_s+p_2\\&v_{u2}\left(f\left(\beta q_2^{\alpha}\right)-\gamma f\left(\beta q_1\right)\right)\geq p_2\end{aligned}$$

These constraints are equivalent to the condition $P_1 \leq p_s \leq P_2$. The optimal price p_2 is its upper bound, $p_2 = \left(p_1 + (1-\delta)\, p_s\right)\left(\frac{f\left(\beta q_2^{\alpha}\right)-\gamma f(\beta q_1)}{(1-\gamma\delta) f(\beta q_1)}\right)$. At this p_2^*, $v_{12} = v_{u2}$. The segment of customers who bought in the second period alone vanishes in this instance, and the resulting scenario belongs to SP 1.

Pricing in SP 3. There is no equilibrium in this SP; Dhebar (1994) proved that when no customer buys in both periods, the firm always behaves opportunistically, causing regret.

Pricing in SP 4. The second period problem and the optimal second period price can be found as follows.

$$\max_{p_2}\left\{p_2\left(1-v_{02}\right)+p_s\left(v_{u2}-v_{02}\right)\right\}$$
$$p_2^* = \frac{f\left(\beta q_2^{\alpha}\right)}{2} - p_s \text{ and } R_2^* = \frac{f\left(\beta q_2^{\alpha}\right)}{4} + p_s\left(\frac{(1-\delta)p_s+p_1}{(1-\gamma\delta)f(\beta q_1)} - 1\right)$$

Based on our solution to the second problem, the first period problem can be written as:

$$\begin{aligned}\Pi^* &= \max_{p_s,p_1}\left\{\left(p_s+p_1\right)\left(1-v_{2u}\right)+\delta R_2^*\right\}\\ &\quad s.t.\quad p_s^*+p_1^* \geq \frac{f\left(\beta q_1\right)}{2}\end{aligned}$$

The unconstrained solution for the problem satisfies

$$p_s^u = \frac{f\left(\beta q_1\right)\left(1-\gamma\delta\right)-2p_1^u}{2\left(1-\delta\right)};\quad p_1^u = \frac{f\left(\beta q_1\right)\left(1-\gamma\delta\right)-2p_s^u\left(1-\delta\right)}{2}$$

However this violates the constraint for SP 4. The constrained optimal solution is

$$\begin{array}{l} p_s^* = \frac{f(\beta q_1)}{2},\, p_1^* = 0,\, p_2^* = \frac{f\left(\beta q_2^\alpha\right) - f(\beta q_1)}{2} \\ \Pi^* = \frac{f(\beta q_1)(1-\delta)(1-\delta(2\gamma-1)) + \delta f\left(\beta q_2^\alpha\right)(1-\gamma\delta)}{4(1-\gamma\delta)} \end{array}$$

A.0.3 Proof of Proposition 3.3.5: Non-Proprietary Architecture

We provide the expressions for the RSI case alone. The expressions for GSI are obtained analogously.

Pricing in SP 1. The second period problem price and profit are $p_2^* = \frac{f\left(q_2^\alpha\right) - \gamma f(q_1)}{2}$ and $R_2^* = \frac{f\left(q_2^\alpha\right) - \gamma f(q_1)}{4}$. The first period optimization problem is

$$\begin{aligned} \Pi^* &= \max_{p_s, p_1} \left\{ (p_s + p_1)(1 - v_{01}) + \delta R_2^* \right\} \\ & s.t. \quad p_s \leq P_1 \end{aligned}$$

The unconstrained solution for this problem is $p_1^u = (f(q_1) - p_s)/2$. When $p_1 = p_1^u$, to satisfy $p_s \leq P_1$ with $p_1 \leq f(q_1)$, we need $\delta(2-\gamma) \geq 1$. This is not satisfied for any $\delta < 1$ and $\gamma > 1$. Therefore, $p_s = P_1$ in equilibrium. The constrained optimal solution is

$$\begin{array}{c} p_1^* = \frac{(1-\gamma\delta) f(q_1) - 2(1-\delta) p_s}{2},\, p_2^* = \frac{f\left(q_2^\alpha\right) - f(q_1)}{2} \\ \Pi^* = \frac{(1-\gamma\delta)((1+\gamma\delta) f(q_1) - 2p_s)}{4} + \delta \frac{\left(f\left(q_2^\alpha\right) - f(q_1)\right)\left(f\left(q_2^\alpha\right) - (2\gamma-1) f(q_1)\right)}{4\left(f\left(q_2^\alpha\right) - \gamma f(q_1)\right)} \end{array}$$

Pricing in SP 2 and SP 3. Arguments in A.0.2 hold. No sub game perfect equilibrium exists in these patterns.

Pricing in SP 4. The optimal price and profit from the second period are $p_2^* = \left(f\left(q_2^\alpha\right) - p_s\right)/2$ and $R_2^* = \frac{\left(f\left(q_2^\alpha\right)-p_s\right)^2}{4f\left(q_2^\alpha\right)}$. The first period problem is

$$\begin{aligned} \Pi^* &= \max_{p_1} \left\{p_1\left(1-v_{u2}\right)+\delta R_2^*\right\} \\ s.t. &\quad p_s \geq P_2 \end{aligned}$$

$p_1^u = \left(\left(1-\gamma\delta\right)f\left(q_1\right) - \left(1-\delta\right)p_s\right)/2$ is the unconstrained solution to this problem. Let $\phi_1 := \frac{(2\gamma\delta-1)f(q_1)f\left(q_2^\alpha\right)}{2\delta f\left(q_2^\alpha\right)-f(q_1)}$ and $\phi_2 := \frac{\gamma f(q_1)f\left(q_2^\alpha\right)}{(1+\delta)f\left(q_2^\alpha\right)-f(q_1)}$ and $\phi_3 := \frac{f(q_1)(1-\gamma\delta)}{(1-\delta)}$. Price p_1^u is feasible if $\phi_3 \geq p_s \geq \phi_2$. When $\phi_2 \geq p_s \geq \phi_1$, the constraint is active and $p_1^c = \left(f\left(q_1\right)\left(f\left(q_2^\alpha\right)+p_s\right) - 2p_s f\left(q_2^\alpha\right)\right)/\left(2f\left(q_2^\alpha\right)\right)$.

For p_s such that $\phi_1 \geq p_s \geq 0$, it is impossible to select a price p_1 that satisfies the timing constraint. That is because, for these values of p_s, we can see that $v_{u2} = \frac{(1-\delta_c)p_s+p_1}{(1-\delta_c)f(q_1)} > 1$ for all permissible values of p_1. The profit maximizing solution in this case is to avoid launching the early version.

$$p_1^* = \begin{cases} \frac{(1-\gamma\delta)f(q_1)-(1-\delta)p_s}{2} & if\ f\left(q_1\right) \geq p_s \geq \phi_2 \\ \frac{f(q_1)\left(f\left(q_2^\alpha\right)+p_s\right)-2p_s f\left(q_2^\alpha\right)}{2f\left(q_2^\alpha\right)} & if\ \phi_2 \geq p_s \geq \phi_1 \\ \text{First version not launched} & if\ \phi_1 \geq p_s \geq 0 \end{cases}$$

$$\Pi^* = p_1^*\left(1 - \frac{p_1^* + \left(1-\delta\right)p_s}{\left(1-\gamma\delta\right)f\left(q_1\right)}\right) + \delta R_2^*$$

A.0.4 Proof of Proposition 3.4.1: Comparison of Architectures

Assumptions: $\alpha = 0$; $\beta = 1$.

1. First, note that the pricing problem for the no-special-upgrade prices solution is same as Problem (3.4,3.5) with the additional constraint that $p_s = 0$. It is now easily verified that $\pi_{MP} > \pi_{IN}$.

2. Finally, note that the non-proprietary solution is a lower bound to the proprietary solution since (a) p_s is fixed at a predetermined value and (b) Revenue from unit sale may be higher by p_s for the proprietary product. Therefore, $\pi_{MP} > \pi_{MN}(p_s)\ \forall\ p_s > 0$

A.0.5 Proof of Proposition 3.4.2: Integrated and Modular Architectures

The first order optimality for optimality of inter-version times (t_d) the MP and IN cases can be written in terms of δ.

$$\frac{\partial \Pi_{MP}(\delta)}{\partial \delta} = 0 \Rightarrow \frac{f(\beta q_2) - f(\beta q_1)}{4} - C_d(q_1, q_2)g'(\delta) = 0$$

$$\frac{\partial \Pi_{IN}(\delta)}{\partial \delta} = 0 \Rightarrow \begin{cases} \frac{f(\beta q_2) - 3f(\beta q_1)}{4} - C_d(q_1, q_2)g'(\delta) = 0 & \text{if } \delta f(\beta q_2) \leq f(\beta q_1) \\ \frac{f(\beta q_2) - (1+2\delta)f(\beta q_1)}{4} - C_d(q_1, q_2)g'(\delta) = 0 & \text{if } \delta f(\beta q_2) > f(\beta q_1) \end{cases}$$

Since $g''(\delta) > 0$, the second order conditions are satisfied. Further, it follows from above that at any δ^*_{MP} that is optimal for the MP architecture, $\frac{\partial \Pi_{IN}(\delta^*_{MP})}{\partial \delta} < 0$. This implies $\delta^*_{MP} > \delta^*_{IN} \Rightarrow t_d^{MP*} < t_d^{IN*}$. Therefore, it is optimal to delay introduction of the advanced product more in the integral system.

A.0.6 Proof of Proposition 3.4.3: Proprietary and Non-Proprietary Architectures

We use C_d to represent $C_d(q_1, q_2)$ in this proof. The expressions below are derived for $\beta = 1$ and $\alpha = 0$, but can be extended to these cases without loss of generality. We have established before that the optimal innovation rate under the MP choice is given by

$$\delta^{MP*} = \delta(t_d^{MP*}) = \frac{f(q_2) - f(q_1)}{4C_d}$$

We consider the two market segmentation patterns possible under MN separately.

SP-1.

$$\Pi^{SP1*} = \frac{(1-\delta)\delta p_s^2}{f(q_1)} + \frac{(1-\delta^2-\delta)f(q_1)+\delta f(q_2)-2(1+\delta-2\delta^2)p_s}{4}$$
$$\delta^{SP1*} = \frac{8p_s^2 + 2p_s f(q_1) + f^2(q_1) - f(q_1)f(q_2)}{2f(q_1)(4p_s - f(q_1) - 2C_d)}$$

Define

$$\begin{aligned}\omega_1 &\doteq f(q_1)f(q_2) - C_d f(q_1) - f^2(q_1)\\ \omega_2 &\doteq f(q_1)\sqrt{c_d^2 - 6C_d(f(q_2) - f(q_1)) + (f(q_2) - f(q_1))^2}\end{aligned}$$

By comparing the expressions above, $\delta^{MP*} \geq \delta^{MN1*}$ if $p_s^{UB1} \leq p_s$ or if $p_s \leq p_s^{LB1}$, where

$$p_s^{UB1} = min\left(\frac{f(q_1)}{2}, \frac{\omega_1 + \omega_2}{8C_d}\right) p_s^{LB1} = max\left(0, \frac{\omega_1 - \omega_2}{8C_d}\right)$$

SP-4. Since the expressions under SP-4 are hard to interpret, we find a weak bound on p_s^{UB4} above which δ^{MP*} is greater and argue that a meaningful bound for p_s^{LB4} may exist below which δ^{MP*} is greater.

$$\Pi^{MN4*} = \begin{cases} \frac{(1-\delta)(f(q_1)-p_s)^2}{4f(q_1)} + \delta R_2^* & \text{, if } f(q_1) \geq p_s \geq \phi_2 \\ R_1^{x*} + \delta R_2^* & \text{, if } \phi_2 \geq p_s \geq \phi_1 \\ \delta R_2^* & \text{, if } \phi_1 \geq p_s \geq 0 \end{cases}$$

where $R_1^{x*} = \frac{\left[p_s(2f(q_2^\alpha)-f(q_1))-f(q_1)f(q_2^\alpha)\right]\left[p_s(f(q_1)-2\delta f(q_2^\alpha))+(2\delta-1)f(q_1)f(q_2^\alpha)\right]}{4(1-\delta)f(q_1)f^2(q_2^\alpha)}$ and $R_2^* = \frac{(f(q_2)-p_s)^2}{4f(q_2)}$

Let $p_s^{UB4} = \frac{f(q_2^\alpha)f(q_1)}{2f(q_2^\alpha)-f(q_1)}$. First, note that if $p_s \geq \frac{f(q_2^\alpha)f(q_1)}{2f(q_2^\alpha)-f(q_1)}$, then $p_s \geq \phi_2 \;\forall\, \delta$. When $f(q_1) \geq p_s \geq \frac{f(q_2^\alpha)f(q_1)}{2f(q_2^\alpha)-f(q_1)}$,

$$\delta^{MP*} = \frac{f(q_2)-f(q_1)}{4C_d} \geq \frac{(f(q_2)-p_s)^2}{4C_d f(q_2)} - \frac{(f(q_1)-p_s)^2}{4C_d f(q_1)} = \delta^{MN4*}$$

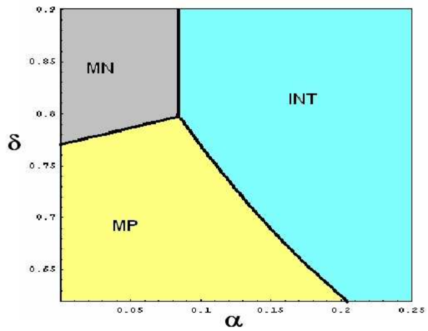
If $\phi_1 \geq p_s \geq 0$, comparison of innovation rates depends on the relative magnitudes of $f(q_1)$, $f(q_2)$ and p_s.

But $lim_{p_s \to 0}\left(\Pi^{MN1*} - \Pi^{MN4*}\right) = \frac{(1-\delta)(f(q_2)-f(q_1)+\delta^2 f(q_1))}{4} > 0$, the firm will prefer SP1 over SP4 segmentation for any δ at this limit. Therefore, as $p_s \to 0$, MP results in faster innovation than MN. Therefore, we know that there exists a bound $p_s^{LB4} \in \left[0, p_s^{LB1}\right]$ such that δ^{MP*} is higher for all $p_s \in \left[0, p_s^{LB4}\right]$.

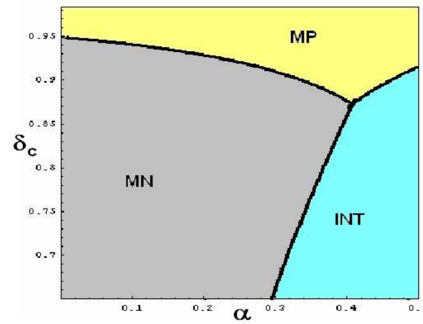
A.1. A Note on the Appropriateness of Product Architectures

While the thrust of this paper is to model and explain the modular upgradable features present found in products in several industrial categories, we also believe that our model easily lends itself to application in consumer markets. However, in evaluating the appropriateness of various product design alternatives to the two situations, some crucial differences must be acknowledged. While discounting rates in industrial markets are derived by considerations of interest rates, individual consumers differ both from the seller and from each other in their temporal preferences. As a result, it may not be reasonable to assume that δ for the firm and its consumers are similar or correlated. Using the following examples, we show the impact of this assumption on our results in Section 3.4.1.

Let δ_c and δ_f denote the per period discount rates for consumers and the firm respectively. In Figure A.1 below, we show the regions in which it is optimal to offer a modular proprietary architecture (MP), a non-proprietary modular design (MN) and an integrated architecture (INT) for the case in which $\delta_c = \delta_f$ and δ_c varies independently from δ_f. In Section 3.4.1, we presented the former case and found that MP is optimal when δ and α are lower. However, when δ_c and δ_f are not correlated, we find that MN could be optimal when δ_c and α are small. In consumer markets, a firm may be able to influence δ_c by tweaking consumer patience through marketing levers such as advertisement campaigns. If consumers become relatively more patient for the new product than the firm, the firm can afford to offer large implicit discounts (high p_s) through the proprietary modular system without significantly affecting the net present cost of these discounts. As a result, the proprietary strategy could become more optimal when customers are relatively more patient than the firm.



$\delta_c \equiv \delta_f$



$\delta_c \neq \delta_f = 0.6$

Figure A.1: Comparing Correlated and Independent Discount Factors

Further, users of consumer products - unlike businesses - also vary widely in their ability to learn by using a product. However, we believe that segmenting consumers based on their ability to learn deserves dedicated attention in a separate work.

Appendix B

Sequential Innovation with Strategic Consumers and Suppliers: Time Inconsistency with Integrated Product Design and Pricing

B.0.1 Proof of Result 4.2.1: Market Segmentation

Proof. Let $P_1 = \frac{q_1 p_2}{q_2 - q_1} - \frac{p_1 + p_{s1} - p_{s2}}{1-\delta}$ and $P_2 = \frac{p_2 q_1 - (p_1 + p_{s1} - p_{s2}) q_2}{q_2 - q_1}$. First consider rapid sequential innovation, where $theta \delta q_2 > q_1$.

Penetration Pricing. When $p_{s2} \leq P_1$, we can show the following relationships regarding the relative location of marginal consumers: $v_{01} \leq \min(v_{0u}, v_{02})$, and $v_{01} \leq v_{u1} \leq v_{12}$. Therefore, the low-end marginal customer buys in the first period alone. The next marginal customer buys in both periods. Further, we know that v_{u1} is the final marginal customer. Therefore, customers in $v \in [0, v_{01})$ do not participate; $v \in [v_{01}, v_{u1})$ buy in the first period; $v \in (v_{1u}, 1]$ buy in the first period and upgrade when the improved product is available.

Skimming. When $p_{s2} \geq P_2$, second period prices are sufficiently low, $v_{02} \leq \min(v_{0u}, v_{01}) \Leftrightarrow$ the low-end marginal customer waits till the second period and buys in the improved version only. Also, $v_{01} \leq v_{u1} \leq v_{12} \Leftrightarrow$The next marginal customer buys in both periods. Further, we know that v_{u2} and v_{02} are the only marginal customers in this range of prices. Therefore, $v \in [0, v_{02})$, do not buy in either period; $v \in [v_{02}, v_{u2})$ buy in the second period; $v \in [v_{u2}, 1]$ buy in the first period and upgrade.

The conditions for achieving *Penetration* and *Skimming* patterns when the product improves at a moderate pace ($\delta q_2 \leq q_1$) can be derived analogously. The demands for the two versions - defined in terms of locations of marginal consumers - do not depend on the depend on the rate of sequential innovation.

□

B.0.2 Market Segmentation for Integrated Products

The maximum revenue for the integrated products (R^*_{Int}) is given by Equation B.1, where R^P_{Int} $\left(R^S_{Int}\right)$ represents the maximum revenue that can be obtained if market segmentation is achieved by aggressive introduction (exclusive introduction) in the first period. These revenues, shown in Equations B.2 and B.3, are obtained by setting $p_s = 0$ and $m = 1$ in the revenue expressions in Equations B.4, B.7, B.5 & B.8.

$$R^*_{Int} \quad = \quad \max\left\{R^P_{Int}, R^S_{Int}\right\} \tag{B.1}$$

where

$$R^P_{Int} = \begin{cases} \left(q_1\left(1-\delta^2\right)+\delta\left(q_2-q_1\right)\right)/4 & if\ \delta q_2 > q_1 \\ \left(\left(q_2^2-q_1^2\right)q_1+\delta\left(q_2-q_1\right)q_2^2\right)/\left(4q_2^2\right) & if\ \delta q_2 \leq q_1 \end{cases} \tag{B.2}$$

$$R^S_{Int} = \begin{cases} \left(q_1\left(1-2\delta\right)+\delta\left(1-\delta\right)q_2\right)/\left(4\left(1-\delta\right)\right) & if\ \delta q_2 > q_1 \\ q_2\left(\delta q_2^2+\left(3\delta-2\right)q_1^2+\left(1-3\delta\right)q_1q_2\right)/\left(4\left(q_2-q_1\right)^2\right) & if\ \delta q_2 \leq q_1 \end{cases} \tag{B.3}$$

By observation, it is clear that $R^P_{Int} > R^S_{Int}$. Therefore, the seller uses Penetration pricing to segment the market with integrated products.

B.0.3 Optimal Prices with AC and PC

Result B.0.1. ***Equilibrium prices with Consistency in Architectural and Pricing Policies***

A seller with architectural and pricing credibility can charge optimal prices p_1 *and* p_2 *that lead to Sub-Game-Perfect equilibrium segmentation of the market if the price of the stable module is limited as below.*

For penetration, $q_1 \geq 2p_s \geq 0$

For skimming, under rapid innovation,

$q_1 \geq p_s \geq (2\delta - 1)\, q_1 q_2 / \left(2q_2 \left(1 - \theta + \delta\theta\right) - \theta q_1\right)$

For skimming, under moderate innovation, $q_1 \geq p_s \geq (2q_1 - q_2)\,/\theta$

Proof. Optimal prices and profits are derived below for both segmentation schemes for the modular architecture. These may be derived for the integrated products by setting $p_s = 0$ and $m = 1$. Since the seller enjoys AC and PC here, the constraints under which we find these prices are $A_1 \doteq A_2$ and $p_2^u = p_2^n = p_2$.

Penetration Pricing

In the following proof, R_t represents the revenue in period t, and R^P and R^S represent net present value of revenue streams from Penetration and Skimming respectively. An asterisk $(*)$, as usual, denotes optimal values.

Pricing under Rapid Innovation, $\delta q_2 > q_1$. The second period problem for the seller can be formulated and solved as below.

$$\max_{p_2} \left\{ p_2 \left(1 - \frac{p_2}{q_2 - q_1} \right) \right\}$$
$$\Rightarrow p_2^* = \frac{q_2 - q_1}{2}$$
$$R_2^* = p_2^*(1 - v_{1u}) = \frac{q_2 - q_1}{4}$$

We now try to solve the first period problem for the seller enforcing the constraint for existence of equilibrium in this region.

$$\begin{aligned}&\max_{p_1} \left\{ p_1 \left(1 - \left(\tfrac{p_1 + p_s}{q_1} \right) \right) \right\} + \delta R_2^* \\ &\text{s.t. } \theta p_s \leq P_1\end{aligned}$$

The unconstrained solution for this problem is given by $p_1^* = \frac{q_1 - p_s}{2}$. When $p_s > q_1$, production in the first period is unprofitable. But this solution satisfies the constraint only when $(2\delta\theta - 1)\, p_s \geq \delta q_1$. Combining these conditions, we require that $(2\delta\theta - 1)\, q_1 \geq \delta q_1$. This cannot be satisfied unless $\theta = \delta = 1$. Therefore, the optimal first period price is $p_1^* = \left((1 - \delta)\, q_1 - 2p_s\, (1 - \theta\delta) \right)/2$. For the first period price to non-negative, we now need $2\,(1 - \delta\theta)\, p_s \leq q_1\, (1 - \delta)$. Note that the condition becomes stronger for higher values of θ; in particular, when $\theta \to 1$, we need $p_s \leq q_1/2$.

$$R^{P*} = \frac{(1 - \theta\delta)\theta\delta p_s^2}{q_1} + \frac{(1 - \delta^2 - \delta)q_1 + \delta q_2 - 2(1 + \delta - 2\theta\delta^2)p_s}{4} \tag{B.4}$$

Pricing under Moderate Innovation, $\delta q_2 \leq q_1$. The second period problem for the seller can be formulated and solved as before.

$$p_2^* = \frac{q_2 - q_1}{2} \text{ and } R_2^* = p_2^*(1 - v_{1u}) = \frac{q_2 - q_1}{4}$$

The first period problem is solved as below

$$\max_{p_1} \left\{ p_1 \left(1 - \left(\frac{p_1 + p_s}{q_1} \right) \right) \right\} + \delta R_2^*$$
$$\text{s.t. } p_s \leq P_2$$

The unconstrained solution for this problem is given by $p_1^{*u} = \frac{q_1 - p_s}{2}$. When $p_1 = p_1^{*u}$, we need $p_s (q_2 - \theta q_1) + q_1 (q_1 - \theta p_s) \leq 0$, which is never satisfied. Therefore, the optimal p_1^* is given by $p_1^* = \frac{(q_2 - q_1)(q_1 - 2p_s) - 2(1-\theta) q_1 p_s}{2\, q_2}$. Obviously, we need $p_s \leq q_1/2$.

$$R^{P*} = \frac{(q_2 + q_1 - 2\theta p_s)(q_2 (q_1 - 2p_s) - q_1 (q_1 - 2\theta p_s)) + 4\delta q_2^2 (q_2 - q_1)}{4q_2^2} \tag{B.5}$$

Skimming

Pricing under Rapid Innovation, $\delta q_2 > q_1$. The second period pricing problem is formulated and solved below.

$$\begin{aligned} \max_{p_2} \{p_2(1 - v_{02})\} = \max_{p_2} \left\{ p_2 \left(1 - \left(\frac{p_2 + \theta p_s}{q_2} \right) \right) \right\} \Rightarrow p_2^* = \frac{q_2 - \theta p_s}{2} \\ R_2^* = p_2^*(1 - v_{02}) = \left(\frac{q_2 - \theta p_s}{2} \right) \left(1 - \frac{q_2 + \theta p_s}{2q_2} \right) = \frac{(q_2 - \theta p_s)^2}{4q_2} \end{aligned} \tag{B.6}$$

The first period pricing problem is

$$\max_{p_1} \{p_1(1 - v_{u2}) + \delta R_2^*\}$$
$$\text{s.t. } \theta p_s \geq P_2$$

The unconstrained solution to this problem is $p_1^{*u} = \frac{(1-\delta)(q_1 - p_s) + \delta(1-\theta)p_s}{2}$. It is feasible if $q_1 \geq p_s \geq \gamma_4$, where $\gamma_4 := \frac{\delta q_2 q_1}{(2-\theta)((1+\delta)q_2 - q_1) + (1-\theta)q_@}$. Let $\gamma_3 := \frac{(2\delta - 1)q_2 q_1}{2q_2(1 - \theta + \theta\delta) - \theta q_1}$. When $\gamma_4 \geq p_s \geq \gamma_3$, the constraint is active and $p_1^{*c} = \frac{q_1 q_2 - p_s(2-\theta)(2q_2 - q_1)}{2q_2}$. Note that p_1^{*c} is always non-negative when $p_s \leq \gamma_4$. If $\gamma_3 \geq p_s \geq 0$, $v_{u2} \geq 1$ even for the constrained optimal value of p_1^{*c}. Therefore, the profit maximizing solution in this case is to avoid launching the early version. In summary, the profits are as follows, where γ_3, γ_4 are defined above, and R_2^* is defined in Equation B.6.

$$R^{S*} = \begin{cases} \frac{((1-\delta)q_1 - p_s(1-\delta(2-\theta)))((1-\delta)q_1 - p_s(1-\delta(3\theta-2)))}{4(1-\delta)q_1} + \delta R_2^* & \text{, if } q_1 \geq p_s \geq \gamma_4 \\ \frac{[(2-\theta)p_s(2q_2-q_1)-q_1q_2]F_S}{4(1-\delta)q_1q_2^2} + \delta R_2^* & \text{, if } \gamma_4 \geq p_s \geq \gamma_3 \\ \delta R_2^* & \text{, if } \gamma_3 \geq p_s \geq 0 \end{cases} \tag{B.7}$$

wehre $F_S = [(2\delta - 1) q_1 q_2 - p_s (2q_2 (1 - \theta + \theta\delta) - (2 - \theta) q_1)]$

Pricing under Moderate Innovation, $\delta q_2 \leq q_1$. As before, the second period price and profit are

$$p_2^* = \frac{q_2 - \theta p_s}{2} \text{ and } R_2^* = p_2^*(1 - v_{02}) = \frac{(q_2 - \theta p_s)^2}{4q_2}$$

The first period pricing problem is

$$\begin{aligned} &\max_{p_1} \{p_1(1 - v_{u2}) + \delta R_2^*\} \\ &\text{s.t. } \theta p_s \geq P_1 \end{aligned}$$

The unconstrained solution to this problem is $p_1^{*u} = \frac{(1-\delta)(q_1-p_s)+\delta(1-\theta)p_s}{2}$. The unconstrained optimum is feasible if $q_1 \geq p_s \geq \gamma_5$, where $\gamma_5 = \frac{(1-\delta)q_1^2}{q_2(1+\delta(2-2\theta))-q_1(1-\theta)(1+2\delta)}$. Also, when $p_s \leq \gamma_6 = (2q_1 - q_2)/\theta$, the constrained price $p_1^{*c} = \frac{(1-\delta)q_1q_2 - p_s(2q_2(1-\theta\delta)-q_1(2-\theta-\theta\delta))}{2(q_2-q_1)}$ is such that $v_{u2} \geq 1$. Therefore, the first version cannot be launched. The optimal profits are summarized below.

$$R^{S*} = \begin{cases} \frac{((1-\delta)q_1 - p_s(1-\delta(2-\theta)))((1-\delta)q_1 - p_s(1-\delta(3\theta-2)))}{4(1-\delta)q_1} + \delta R_2^* & \text{, if } q_1 \geq p_s \geq \gamma_5 \\ \frac{(q_2+\theta p_s-2q_1)((1-\delta)q_1q_2 - p_s(2q_2(1-\theta\delta)-q_1(2-\theta-\theta\delta)))}{4(q_2-q_1)^2} + \delta R_2^* & \text{, if } \gamma_5 \geq p_s \geq \gamma_6 \\ \delta R_2^* & \text{, if } \gamma_6 \geq p_s \geq 0 \end{cases} \tag{B.8}$$

$\square$

B.0.4 Proof of Proposition 4.2.2

Proof. **a) Architectural Inconsistency**

We prove part this part of the result by contradiction. Consider settings in which profit of a seller (with AC) is maximized through Skimming.

Open-Sourcing. In the second period, both repeat and new buyers buy the improved product. While new buyers expend θp_s of their budget toward the stable module, repeat buyers purchase only the improving module. By retaining the product's modularity, the seller makes $(q_2 - \theta p_s)^2 / 4q_2$ through the improving module alone in the second period. However, switching to an integrated design would increase the revenue to $q_2/4$. As a result, the seller is unable to credibly commit to modular upgradability of the advanced version under skimming.

Specialist-Sourcing. The demand for the improving and stable module sellers in the second period are given, respectively, by $1 - (p_2 + p_{s2}) / q_2^M$ and $v_{2u} - (p_2 + p_{s2}) / q_2^M$, where v_{2u} is the marginal consumer who purchased the first version. The Nash equilibrium prices of the two firms are $p_2^* = q_2^M (2 - v_{2u}) / 3$ and $p_{s2}^* = q_2^M (2v_{2u} - 1) / 3$. Note that we need $v_{2u} > .5$ for feasibility. The corresponding profits for the seller is $R_2^* = q_2^M (2 - v_{2u})^2 / 9$. However, if the seller integrates the product in the second period, the seller would obtain $q_2^I/4$, where q_2^I is the integrated advanced version's quality (For $\phi > 1$, $q_2^M > q_2^I$). Since $v_{2u} < .5$, we know that $R_2^* \leq q_2 (2 - .5)^2 / 9 = q_2(2.25/9) = q_2/4$. Therefore, for reasonable values of ϕ, the seller prefers to switch to an integrated version in the second period.

b) Pricing Inconsistency

Suppose customers in $(\hat{v}, 1]$ purchase in the first period, and those in $(\tilde{v}, 1]$ do so with the intention of upgrading under the profit maximizing price-discrimination approach ($\hat{v} \leq \tilde{v}$). First period marginal consumers in $[\hat{v}, \hat{v} + \epsilon)$ prefer to purchase a product of quality q_1 instead of waiting for the improved product ($\hat{v} + \epsilon \leq \tilde{v}$). In the second period, the seller may elect to sell the improved version at price p_2^n to some or all consumers in $[\underline{v}, \hat{v})$. In order to market the improved product to consumers in $[\underline{v}, \hat{v})$, the maximum price p_2^n is less than $\underline{v}q_2 - p_s$. This anticipated lowering of second period price makes purchasing in the first period irrational for consumers in $[\hat{v}, \hat{v} + \epsilon)$. Offering special upgrade prices, therefore, is an infeasible strategy under penetration pricing. □

B.0.5 Proof of Proposition 4.4.1

We first state and prove Lemma B.0.2 below.

Lemma B.0.2. *In any penetration pricing demand profile, the equilibrium second period price of the stable module, p_{s2}, is zero.*

Proof. If the products are launched to create a penetration demand profile, no new consumers enter the market in the second period. Setting a positive price p_{s2} in the second period is sub-optimal for the stable module manufacturer when demand for stable modules is 0. Therefore, to entice the marginal consumer v_{01} to enter the market, he drops his price p_{s2} to 0. $\square$

Due to Lemma B.0.2 above, we set $p_{s2} = 0$ for penetration pricing. We know that the optimal improving module price in penetration pricing in the second period is given by $p_2^* = (q_2 - q_1)/2$. To ensure that the marginal consumer v_{01} does not consider entering the market even when the stable module manufacturer sets $p_{s2} = 0$, we need $v_{01} q_2 \leq p_2 + p_{s2}$. Equation 4.10 is obtained by setting $p_2 = p_2^*$ and $p_{S2} = 0$ in this inequality. The result does not depend on the rate of innovation q_2/q_1.

B.0.6 Proof of Proposition 4.4.2

Proof. For $\delta q_2^M > q_1^M$, by setting $\theta = 0$ in Equation 4.6, we obtain

$$\bar{p}_1|_{\theta=0} = \frac{(1-\delta)\, q_1^M - 2p_s}{2}$$

Clearly, the the right hand side in Equation B.9 below is positive under rapid innovation.

$$\hat{p}_1 - \bar{p}_1|_{\theta=0} = \frac{\left(\delta q_2^M - q_1^M\right) q_1^M}{2q_2^M} \tag{B.9}$$

$\square$

B.0.7 Proof of Proposition 4.4.3

Proof. Let Π_x^A represent the profit for the party x under architecture architecture A, where $A \in \{I, M\}$ and $x \in \{IM, SM\}$. By definition, a Nash-

Bargaining equilibrium price p_s^* maximizes the product $\left(\Pi_{IM}^{M} - \Pi_{IM}^{I}\right)\Pi_{SM}^{M}$ (Fudenberg and Tirole, 1991).

For any p_s, Π_{IM}^{M} is obtained by setting $p_1 = \max\{\hat{p}_1, p_1^*\}$ in Equations B.4 and B.5 above. The profit Π_{IM}^{I} is obtained by setting $p_s = 0$ in the same equations. For a given p_s, the stable module manufacturer's profit $\Pi_{SM}^{M} = p_s\left(1 - v_{01}\right)$.

The equilibrium p_s^* and additional profit $\Delta\Pi_I$ are now obtained in a straightforward manner. □

B.0.8 Proof of Proposition 4.5.1

Proof. Here, we prove the existence of $\tilde{q}_s$ for specialist-sourcing. The proof for open-sourcing is analogous.

First we characterize the optimal development investment and q_{2c}^* under rapid and moderate rates of sequential innovation. The optimal q_{2c}^* is given by q_{2c}^r (or q_{2c}^m) in Equation B.10 below if $\delta q_2^{*M} > q_1^M$ (or $\delta q_2^{*M} \leq q_1^M$).

$$\begin{aligned} q_{2c}^r &= q_{1c} + \frac{\alpha\delta}{8C_D} \\ q_{2c}^m &= \arg\max\left\{\Pi_{IM}^{Mm} - C_D\left(q_{2c}^2 - q_{1c}^2\right)\right\} \end{aligned} \tag{B.10}$$

where Π_M^{Mm} is obtained by setting $p_s = p_s^*$ in Equation B.5.

Clearly, q_{2c}^r is independent of q_s. While we are unable to derive a closed form expression for q_{2c}^m, it is possible to show the following

$$\left.\frac{\partial^2\left\{\Pi_{IM}^{Mm} - C_D\left(q_{2c}^2 - q_{1c}^2\right)\right\}}{\partial q_{2c}\partial q_s}\right|_{q_s=0} = \frac{3(1-\alpha)(1+m\phi)(q_{2c}-q_{1c})q_{1c}^2}{4q_{2c}^4} > 0 \tag{B.11}$$

Since q_{2c}^{m} is defined by $\partial_{q_{2c}}\left\{\Pi_{IM}^{Mm} - C_D\left(q_{2c}^2 - q_{1c}^2\right)\right\} = 0$, we know that q_{2c}^{m} is increasing in q_s for small values of q_s (Topkis, 1998). Now we define $\bar{q}_s\left(C_D\right)$ as follows.

$$\bar{q}_s\left(C_D\right) \;=\; \begin{cases} 0 & \text{if} \quad \delta\left(\alpha q_{2c}^{m} + (1-\alpha)\, m\phi q_s\right) > F_\phi \\ \frac{\alpha\left(\delta q_{2c}^{m} - q_{1c}\right)}{(1-\delta)(1-\alpha)m\phi} & \text{if} \quad \delta\left(\alpha q_{2c}^{m} + (1-\alpha)\, m\phi q_s\right) \leq F_\phi \end{cases} \tag{B.12}$$

where $F_\phi = \alpha q_{1c} + (1-\alpha)\, m\phi q_s$. When $q_s < \bar{q}_s$, it follows from the definitions above that $\delta q_2^M > q_1^M$, and we also know from Equation B.10 that q_{2c}^{*} is independent of q_s. Otherwise, $q_{2c}^{*} = q_{2c}^{m}$, which we know is increasing in q_s for small values of q_s. □

Appendix C

Channels for Sequential Innovation: The Role of "Infermediaries"

C.0.9 Proof of Result 5.3.1: Pricing without Infermediary

Proof. Let $\beta_u = \alpha_u \beta + (1 - \alpha_u)$. We will find prices by backward induction beginning in the second period.

AA. All consumers upgrade their products in the second period. To ensure low-end consumers upgrade, the manufacturer sets $p_h = \gamma - 1$. The first period price p_l should meet the following two conditions.

$$\begin{aligned} \beta\left((1-\delta)+\delta\gamma\right)-\left(p_l+\delta p_h\right) &\geq \max\left\{\delta\left(\beta\gamma-p_h\right),0\right\} \\ \beta_u\left((1-\delta)+\delta\gamma\right)-\left(p_l+\delta p_h\right) &\geq \max\left\{\delta\left(\beta_u\gamma-p_h\right),0\right\} \end{aligned}$$

Although $\beta_u \gamma > p_h$, if uncertain consumers do not buy in the first period, the manufacturer could charge $\beta_u \gamma$ in the second period. Therefore, the price of the low-end product is $p_l = \beta_u\left(1+\gamma\left(\delta-1\right)\right)-\delta\left(\gamma-1\right)$.

AH. As all high-end consumers upgrade in the second period, $p_h = \beta\left(\gamma-1\right)$. In the first period, the manufacturer sets p_l to entice uncertain consumers. The participation constraint for these consumers may be written as

$$\beta_u\left(1-\delta\right)+\delta\left(\alpha_u\left(\beta\gamma-p_h\right)+\left(1-\alpha_u\right)\right) \geq p_l$$

Substituting for p_h, it can be shown that $p_l = \beta_u$.

HA. Suppose upgrade prices are offered. In the second period, uncertain consumers are willing to pay $p_h = \beta_u\gamma$, while upgrading high-end consumers pay $p_u = \beta(\gamma - 1)$. Naturally, this can occur only if $\beta(\gamma - 1) < \beta_u\gamma$, which occurs only if $\alpha_u > 1 - \frac{\beta}{\gamma(\beta-1)}$. In the first period, the participation constraint for the high-end segment is

$$\beta(1 - \delta + \delta\gamma) - p_l - \delta p_u \geq \delta\beta\gamma - \delta p_h$$

This gives $p_l = \beta - \delta\gamma(\beta - \beta_u)$.

Suppose, upgrade prices cannot be offered. In the second period, both upgraders and new buyers pay $p_h = \beta_u\gamma$. Applying a similar participation constraint in the first period for the high-end consumers, $p_h = (1 - \delta)\beta$.

HH. Upgrade price in second period $p_h = \beta(\gamma - 1)$ since these high-end consumers already own the product. Note that the manufacturer would set $p_h = \beta\gamma$ if they do not buy in the first period. The participation constraint for the consumer is

$$\beta(1 - \delta + \delta\gamma) - p_l - \delta\beta(\gamma - 1) \geq 0$$

leading to a first period price of $p_l = \beta$. □

C.0.10 Proof of Corollary 5.3.2: Profits without Infermediary

Proof. Without an infermediary, the profits are simply obtained as $\pi_{xy} = n_l p_l + \delta(n_h p_h + n_u p_u)$ (Equation 5.2). The prices in each approach are derived above. The number of consumers n_l, n_h and n_u for each approach is given below.

AA. $n_l = n_u = 1$ and $n_h = 0$

AH. $n_l = 1$ and $n_u = \alpha + (1-\alpha)\,\alpha_u$; $n_h = 0$

HA. $n_l = n_u = \alpha$ and $n_h = 1-\alpha$

HH. $n_l = n_h = 1$ and $n_u = 0$

The profit expressions obtain by substitution. □

C.0.11 Thresholds for Discussion withouth Infermediary

I first define the following thresholds.

$\hat{\alpha}_u$	$\frac{\delta\gamma-1}{\delta(\gamma-1)}$
α_{u1}	$\frac{(\beta-1)\gamma-\beta}{(\beta-1)\gamma}$
α_{u2}	$\frac{(\beta-1)-\delta}{(\beta-1)}$
α_1	$1/\beta$
α_2	$\frac{1-\delta\gamma+\alpha_u(\beta(1-\delta)+\gamma\delta-1)}{\beta(\alpha_u\delta(\gamma-1)-(\gamma\delta-1))}$
α_3	$\frac{\gamma(1+\alpha_u(\beta-1))}{\beta(\gamma-1)}$
α_4	$\frac{1+\alpha_u((\beta-1)+\delta\beta(\gamma-1))}{\beta(1+\delta(\alpha_u(\gamma-1)-1))}$
α_5	$\frac{1+\alpha_u(\beta-1)}{\beta}$

Table C.1: Thresholds on α and α_u without the infermediary

Lemma C.0.3 outlines the basic logic of the thresholds in Table C.1.

Lemma C.0.3. Thresholds without Infermediary

1. AA is preferred over AH iff $\alpha > \alpha_1$

2. HA is preferred over AH iff $\alpha > \alpha_2$

3. HH is preferred over HA iff $\alpha > \alpha_3$

4. HH is preferred over AH iff $\alpha > \alpha_4$

5. HA is preferred over AA iff $\alpha > \alpha_5$

Proof. The proof is obtained by simply comparing the profits from Corollary 5.3.2. □

C.0.12 Proof of Proposition 5.3.3: Profits without Infermediary

Proof. The following relationships between the thresholds can be established.
1. If $\gamma\delta > 1$ and $\alpha_u < \hat{\alpha}_u$, then $\alpha_2 < \alpha_1$ and $\alpha_5 < \alpha_1$. Futhermore, if $\alpha_u > \alpha_{u1}$, $\alpha_5 > 1$. Therefore

a. If $\alpha_u < \alpha_{u1}$: AA is used for $\alpha \in [0, \alpha_5)$, HA is used for $\alpha \in [\alpha_5, \alpha_3)$ and HH is used for $\alpha \in [\alpha_3, 1]$

b. If $\alpha_u > \alpha_{u1}$: AA is used for $\alpha \in [0, \alpha_5)$, HA is used for $\alpha \in [\alpha_5, 1]$.

2. If $\gamma\delta < 1$ or $\alpha_u < \hat{\alpha}_u$, then $\alpha_5 > \alpha_1$ and $\alpha_4 < \alpha_2$. Futhermore, if $\alpha_u > \alpha_{u2}$, $\alpha_4 > 1$. Therefore

a. If $\alpha_u < \alpha_{u2}$: AA is used for $\alpha \in [0, \alpha_1)$, AH is used for $\alpha \in [\alpha_1, \alpha_4)$ and HH is used for $\alpha \in [\alpha_4, 1]$

b. If $\alpha_u > \alpha_{u2}$: AA is used for $\alpha \in [0, \alpha_1)$, AH is used for $\alpha \in [\alpha_1, 1]$. □

C.0.13 Proof of Proposition 5.3.4: Product Introduction Through Infermediary

Proof. Suppose the infermediary is used but only to reveal preferences to consumers in the second period. Clearly, this occurs only if the manufacturer has sold the basic product only to high-end consumers. The segment of high-end consumers who are unaware of their valuations, $\alpha_u (1 - \alpha)$, purchase the product in the second period only. Since it is optimal to sell both products to high-end consumers who are previously aware of their valuations, it is also optimal to sell both versions to the unware high-end segment also. Therefore using the infermediary in the second period alone is inefficient.

Suppose the infermediary is used in the first period to sell the basic product to low-end consumers also. Their valuation based on which the manufacturer can set p_l is only 1, whereas by using the regular channel the price p_l could be as high as β_u (> 1). Therefore, the infermediary never sells to the low-end consumer.

HA. The optimal second period price $p_h = \gamma$ and upgrade price, if offered, is $p_u = \beta (\gamma - 1)$. Backtracking to the high-end segment's first period participation constraint, we obtain $p_l = (1 - \delta) \beta$ (or $\beta - \delta\gamma (\beta - 1)$ if upgrade price is offered).

HH. This derivation is similar to Result 5.3.1. □

C.0.14 Thresholds for Discussion with Infermediary

I first define the following thresholds.

α_{u3}	$\frac{\delta}{1+\delta(\gamma-1)}$
α_{i1}	$\frac{-1+\delta-\delta\gamma+\alpha_u(1+\delta(\gamma-1)-\beta m)}{\beta(-1+\delta-\delta\gamma+\alpha_u(1+\delta(\gamma-1)-m))}$
α_{i2}	$\frac{1-\alpha_u+\alpha_u\beta m}{\beta-\alpha_u+\alpha_u\beta m}$
α_{i3}	$\frac{-\delta\gamma+\alpha_u(\delta\gamma+\beta(1-\delta-m))}{\beta(-\delta\gamma+\alpha_u(\delta\gamma+1-\delta-m))}$
α_{i4}	$\frac{\alpha_u(1+\delta(\gamma-1)-m)}{-\delta+\alpha_u(1+\delta(\gamma-1)-m)}$
α_{ia1}	$\frac{1-\delta+\alpha_u(\gamma\delta(\beta-1)-(1-\delta-m))}{(1-\alpha_u)\beta(1-\delta)-\alpha_u m}$
α_{ia2}	$\frac{1-\delta\gamma+\alpha_u(\delta\beta\gamma+m-1)}{(1-\alpha_u)\beta(1-\delta)-\alpha_u m}$
α_{ia3}	$\frac{-\delta\gamma+\beta(\gamma\delta-1+\delta)+m}{\beta(-1+\delta)+m}$
α_{ia4}	$\frac{-\delta\gamma+\alpha_u(m-\beta(1-\delta))}{-\delta\beta(\gamma-1)+\alpha_u(m-\beta(1-\delta))}$

Table C.2: Thresholds on α with infermediary

Lemma C.0.4 outlines the basic logic of the thresholds in Table C.2.

Lemma C.0.4. Thresholds without Infermediary

1. HH with infermediary is preferred over AA, AH, HA and HH without infermediary iff $\alpha >\alpha_{i1}$, α_{i2}, α_{i3} *and* α_{i4} *respectively.*

2. AH with infermediary is preferred over AA, AH, HA and HH without infermediary iff $\alpha >\alpha_{ia1}$, α_{ia2}, α_{ia3} *and* α_{ia4} *respectively.*

Proof. The proof is obtained by simply comparing the profits derived from Proposition 5.3.4 with corresponding profits from Corollary 5.3.2. □

C.0.15 Proof of Proposition 5.3.5: Profits with Infermediary

Proof. The following relationships between the thresholds can be established. 1. If $\gamma\delta > 1$ and $\alpha_u < \hat{\alpha}_u$, then $\alpha_{i1} < \alpha_5$ and $\alpha_{i1} < \alpha_{1a1}$. Also $\alpha_{i3} < \alpha_{i1}$. Therefore, AA is used for $\alpha \in [0, \alpha_{i1})$, HH with infermediary is used for $\alpha \in$

$[\alpha_{i1}, \alpha_{i4})$ and HH is used for $\alpha \in [\alpha_{i4}, 1]$.

2. If $\gamma\delta < 1$ or $\alpha_u < \hat{\alpha}_u$, then $\alpha_1 < \alpha_{i1}, \alpha_{ia1}$ and $\alpha_{i2} < \alpha_4$. Therefore, AA is used for $\alpha \in [0, \alpha_1)$, AH is used for $\alpha \in [\alpha_1, \alpha_{i2})$, HH with the infermediary for $\alpha \in [\alpha_{i2}, \alpha_{i4})$ and HH is used for $\alpha \in [\alpha_{i4}, 1]$.

Futhermore, if $\alpha_u > \alpha_{u3}$, $\alpha_{i4} > 1$. Therefore, if $\alpha_u > \alpha_{u3}$, HH with the direct channel is never suitable. $\square$

Bibliography

ASML (2001). Asml financial report. Available at http://www.asml.com.

ASML (2005). ASML Annual Report. Available at http://www.asml.com.

Baldwin, C. Y. and K. B. Clark (1997). Managing in an Age of Modularity. *Harvard Business Review 75*(5), 84–93.

Baldwin, C. Y. and K. B. Clark (2000). *Design Rules: The Power of Modularity*, Volume 1. Cambridge, MA: MIT Press.

Bhaskaran, S. R. and S. M. Gilbert (2005). Selling and leasing strategies for durable goods with complementary products. *Management Science 51*(8), 1278–1290.

Bhattacharya, S., V. Krishnan, and V. Mahajan (2003). Operationalizing technology improvements in product development decision-making. *European Journal of Operational Research 149*(1), 102–130.

Bulow, J. I. (1982). Durable Goods Monopolists. *Journal of Political Economy 90*(2), 314–332.

Business Week (March 27, 2006). Speed demons. how smart companies are creating new products - and whole new business - almost overnight.

Carroll, J. D. and P. E. Green (1995). Guest editorial: Psychometric methods in marketing research: Part i, conjoint analysis. *Journal of Marketing Research 32*(4), 385–391.

Cattani, K., W. Gilland, S. Heese, and J. M. Swaminathan (2006). Boiling frogs: Pricing strategies for a manufacturer adding a direct channel that competes with the traditional channel. *Production and Operations Management 47*(2), 40–57.

Chuma, H. and Y. Aoshima (2003, January). Determinants of microlithography industry leadership. RIETI Discussion Paper Series 03-E-003.

Coase, R. H. (1972). Durability and Monopoly. *Journal of Law and Economics 15*(1), 143–149.

Cremer, J. (1984). On the Economics of Repeat Buying. *The Rand Journal of Economics 15*(3), 396–403.

Desai, P., S. Kekre, S. Radhakrishnan, and K. Srinivasan (2001). Product Differentiation and Commonality in Design: Balancing Revenue andCost Drivers. *Management Science 47*(1), 27–51.

Dhebar, A. (1994). Durable- Goods Monopolists, Rational Consumers, and Improving Products. *Marketing Science 13*(1), 100–120.

Dhebar, A. (1996, Winter). Speeding High-Tech Producer, Meet the Balking Consumer. *Sloan Management Review 37*(2), 37–49.

Dutch News Digest (October 21, 2003). Dutch asml receives orders for twinscan xt - 1250 lithography scanner.

Erat, S. and S. Kavadias (2006). Introduction of New Technologies to Competing Industrial Consumers. *Management Science 52*(11), 1675–1688.

Fisher, M., K. Ramdas, and K. Ulrich (1999). Component Sharing in the Management of Product Variety: A Study of AutomotiveBraking Systems. *Management Science 45*(3), 297–315.

Fishman, A. and R. Rob (2000). Product Innovation by a Durable-Good Monopolist. *RAND Journal of Economics 31*(2), 237–252.

Fudenberg, D. and J. Tirole (1991). *Game Theory*. The MIT Press.

Fudenberg, D. and J. Tirole (1998). Upgrades, Tradeins, and Buybacks. *RAND Journal of Economics 29*(2), 235–258.

Gabaix, X. and D. Laibson (2006, May). Shrouded attributes, consumer myopia, and information suppression in competitive markets. *The Quarterly Journal of Economics*, 505–540.

Garud, R. and A. Kumaraswamy (1993). Changing Competitive Dynamics in Network Industries: An Exploration of SunMicrosystems' Open Systems Strategy. *Strategic Management Journal 14*(5), 351–369.

Graves, S. B. (1989). The time-cost tradeoff in research and development: A review. *Engineering Costs Production Economics 16*, 1–9.

Henderson, R. M. and K. B. Clark (1990). Architectural Innovation: The Reconfiguration of Existing Product Technologiesand the Failure of Established Firms. *Administrative Science Quarterly 35*(1), 9–30.

Hoppe, H. C. (2002). The Timing of New Technology Adoption: Theoretical Models and EmpiricalEvidence. *The Manchester School 70*(1), 56–76.

Kekre, S. and K. Srinivasan (1990). Broader product line: A necessity to achieve success? *Management Science 36*(10), 1216–1231.

Kühn, K.-U. and A. J. Padilla (1996). Product line decisions and the coase conjecture. *The RAND Journal of Economics 27*(2), 391–414.

Kim, K. and D. Chhajed (2000). Commonality in product design: Cost saving, valuation change and cannibalization. *European Journal of Operational Research 125*(3), 602–621.

Kornish, L. J. (2001). Pricing for a Durable-Goods Monopolist Under Rapid Sequential Innovation. *Management Science 47*(11), 1552–1561.

Krishnan, V. and K. T. Ulrich (2001). Product development decisions: A review of the literature. *Management Science 47*(1), 1–21.

Krishnan, V. and W. Zhu (2006). Designing a Family of Development-Intensive Products. *Management Science 52*(6), 813–825.

Lal, R. (1990). Improving channel coordination through franchising. *Marketing Science 9*(4), 299–318.

Langlois, R. N. and P. R. Robertson (1992). Networks and Innovation in a Modular System: Lessons from the microcomputerand stereo equipment industries. *Research Policy 21*, 297–313.

Lariviere, M. and A. Alexandrov (2007). Are reservations recommended? Working Paper, Northwestern University.

Mikkola, J. H. and O. Gassmann (2003). Managing Modularity of Product Architectures: Toward an Integrated Theory. *IEEE Transactions on Engineering Management 50*(2), 204–218.

Milgrom, P. (1981). Good news and bad news: Representation theorems and applications. *Bell Journal of Economics 12*, 380–391.

Moorthy, K. S. and I. P. L. Png (1992). Market Segmentation, Cannibalization, and the Timing of Product Introductions. *Management Science 38*(3), 345–359.

Morris, C. R. and C. H. Ferguson (1993). How Architecture Wins Technology Wars. *Harvard Business Review 71*(2), 86–96.

Mussa, M. and S. Rosen (1978). Monopoly and Product Quality. *Journal of Economic Theory 18*(2), 301–317.

Nelson, P. (1970). Information and consumer behavior. *The Journal of Political Economy 78*(2), 311–329.

Newsweek (March 25, 2002). Upholding Moore's Law.

PC Magazine (May 6, 2003). Coming Attractions.

Ramachandran, K. and V. Krishnan (2007). Design architecture and introduction timing for rapidly improving industrial products. Forthcoming in Manufacturing and Service Operations Management.

Sanchez, R. (1999). Modular Architectures in the Marketing Process. *Journal of Marketing 63*(Special Issue), 92–111.

Sanderson, S. and M. Uzumeri (1995). Managing product families: The case of the Sony Walkman. *Research Policy 24*(5), 761–782.

Simon, H. A. (1969). *The Sciences of the Artificial*. Cambridge, MA: MIT Press.

Stokey, N. L. (1979). Intertemporal Price Discrimination. *The Quarterly Journal of Economics 93*(3), 355–371.

Stokey, N. L. (1988). Learning by Doing and the Introduction of New Goods. *Journal of Political Economy 96*(4), 701–717.

Su, X. (2006, June). Inter-temporal pricing with strategic customer behavior. Forthcoming in Management Science.

The News & Observer (February 9, 2006). Ibm's blade computer products make impact.

The Wall Street Journal (September 10, 1991). Computers: Compaq Chases Rivals in Move To Modular PCs.

Topkis, D. M. (1998). *Supermodularity and Complementarity.* Princeton University Press.

Ulku, S. and G. Schmidt (2005). Matching Product Architecture and Supply Chain Design. Working Paper, Georgetown University.

Ulrich, K. (1995). The role of product architecture in the manufacturing firm. *Research Policy 24*(3), 419–440.

Ulrich, K. T. and D. Ellison (1999). Holistic Consumer Requirements and the design-select decision. *Management Science 45*(5), 641–658.

Villas-Boas, M. (1998). Product Line Design for a Distribution Channel. *Marketing Science 17*(2), 156–169.

Waldman, M. (1996). Planned Obsolescence and the R and D Decision. *RAND Journal of Economics 27*(3), 583–595.

Xia, Y. and S. M. Gilbert (2007). Strategic interactions between channel structure and demand enhancing services. *European Journal of Operational Research 181*(1), 252–265.

Xie, J. and S. M. Shugan (2001). Electronic tickets, smart cards, and online prepayments- when and how to advance sell. *Marketing Science 20*, 219–243.

Young, E. . (2001). Global online retailing: An ernst & young special report. Technical report, Ernst & Young.

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